THE UNIVERSITY OF ALBERTA

SLOPE EVOLUTION

ON

RECESSIONAL MORAINES

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled Slope Evolution on Recessional Moraines, submitted by David Michael Welch in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

Theoretical and field studies of slope development have contributed much to the understanding of geomorphic processes and the sequential change of slope profiles. Such work has, however, been confined to relative time scales only, so that little is known of how fast developments take place, or to what extent rate of slope change varies through time.

This thesis is a study of twenty-five recessional moraines in front of the Athabaska Glacier, Jasper National Park, Alberta. These moraines were left behind as the glacier retreated from the position of the maximum Little Ice Age advance (ca. 1,000 A.D. to ca. 1,750 A.D.). Accurate dates are available for each moraine, the oldest of which was deposited around 1880. The moraines are of two main sizes; some reach twenty to fifty feet in height, while others are only a few feet high. Slopes were measured by Brunton compass on the larger moraines. Detailed cross sections of the smaller moraines were surveyed with the aid of an Abney level. From this data, scaled-down topographic profiles were drawn. Slope measurements for these smaller moraines were taken from the constructed profiles. For each moraine, the slope observations were averaged into various parameters such as mean and median slope value, and the distribution of slope readings between zero and ninety degrees.

The moraines consist of debris ranging from clay sized particles to boulders of five feet diameter, although for the most part the stones have a general maximum size of three to four inches. The moraines may therefore be regarded as having essentially constant geology. Furthermore, all have been and are subject to a similar environment and processes. The

study of slopes on moraines of varying ages can then substitute for the study of slope evolution on a given moraine over a passage of years.

Frost-heaving, rainwash and settling under the action of gravity are the main processes at work. These and other processes work at first on piles of loose, saturated debris having no characteristic slope angle or form. Through time the till dries out and becomes more compact and smooth. In reaching equilibrium with their new environment, the moraines trend toward slopes of twenty-five to thirty degrees, with narrow summits of convex form. Changes in topography are paralleled by a general reduction of clay content. General increases of stone sphericity and roundness do occur through time, but these changes are small and inconsistent.

No two slope parameters change at the same rate, but in all cases developments are relatively rapid at first and then progressively slower. As much change takes place in the first half-dozen years as during the remaining eighty years of the current time span of moraines at the Athabaska Glacier.

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CHAPTER I

BACKGROUND AND DEFINITION

Many geomorphologists have been concerned with problems of slope development. Often the arguments were based on theory or on subjective landscape impressions. In recent years researchers have measured slope profiles and occasionally relative time sequences of slope development have been available. This thesis provides measurements of slopes for known periods of development and tests whether progressive changes of form do or do not take place. The nature and place of the study were determined so that absolute dates of slopes were available.

The history of studies of slope evolution is discussed adequately by B.W. Sparks,[1] W.D. Thornbury[2] and C.A.M. King.[3] Various symposia and periodical articles have covered more specific points, for example K. Bryan[4] and M. Simons.[5] More recently A.N. Strahler has led a move towards quantitative field studies and a dynamic concept of slope

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1 Sparks, B.W., Geomorphology, Longmans (1961), 371 pp.

2 Thornbury, W.D., Principles of Geomorphology, Wiley (1954), 618 pp.

3 King, C.A.M., Techniques in Geomorphology, Arnold, (1966), 342 pp.

4 Bryan, K., (arranger) "Symposium on Geomorphology in Honour of the One Hundredth Anniversary of the Birth of William Morris Davis." A.A.A.G. (1950): Contributions by L. Martin, C. A. Cotton, H. Baulig, K. Bryan, A.N. Strahler and L. C. Peltier.

5 Simons, M., "The Morphological Analysis of Landforms", Trans. Inst. British Geographers (1962) No. 31, pp. 1 - 14.

evolution.[6] Three articles in particular were embryonic to this thesis. These are by R.A.G. Savigear,[7] A. Young[8] and C. J. Heusser.[9]

Young traversed thirty-three slope profiles in three areas of England and Wales. His interest centred on maximum angles, degree of curvature, and the depth and particle reduction of regolith in relation to position on the slope. In each of the three regions slopes were surveyed for different stages of river basin development. For one of these, the Heddon Basin on Exmoor, eight profiles were scaled down to equal height and plotted graphically so as to avoid overlap: all but one can be fitted to a common base (Figure 1). Assuming that slopes in this area are developing under fluvial erosion, as opposed to accumulation, then this series of slopes may be likened to a model of slope evolution.

In his concluding section Young modifies his diagram (Figure 1) to a generalization of slope development for the three areas. In selecting the profile sites he made no attempt to predetermine the stages of slope evolution. Only after the profiles were superimposed did he make the arbitary assumption that they would develop in such a manner. The main conclusion is that some initial parallel retreat of the upper part of a slope must occur if a concavity is to be produced; however, overall development is by decline of angle. Young further

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6 Strahler, A.N., see K. Bryan, op.cit..

7 Savigear, R.A.G., "Some Observations on Slope Development in South Wales," Trans. Inst. British Geographers (1952) No. 18, pp. 31 - 52.

8 Young, A., "Some Field Observations of Slope Form and Regolith, and their Relation to Slope Development," Trans. Inst. British Geographers (June 1963), No. 32, pp. 1 - 39.

9 Heusser, C.J., "Post Glacial Environments in the Canadian Rocky Mountains." Ecological Monographs, (1956), No. 26, pp. 263 - 302.

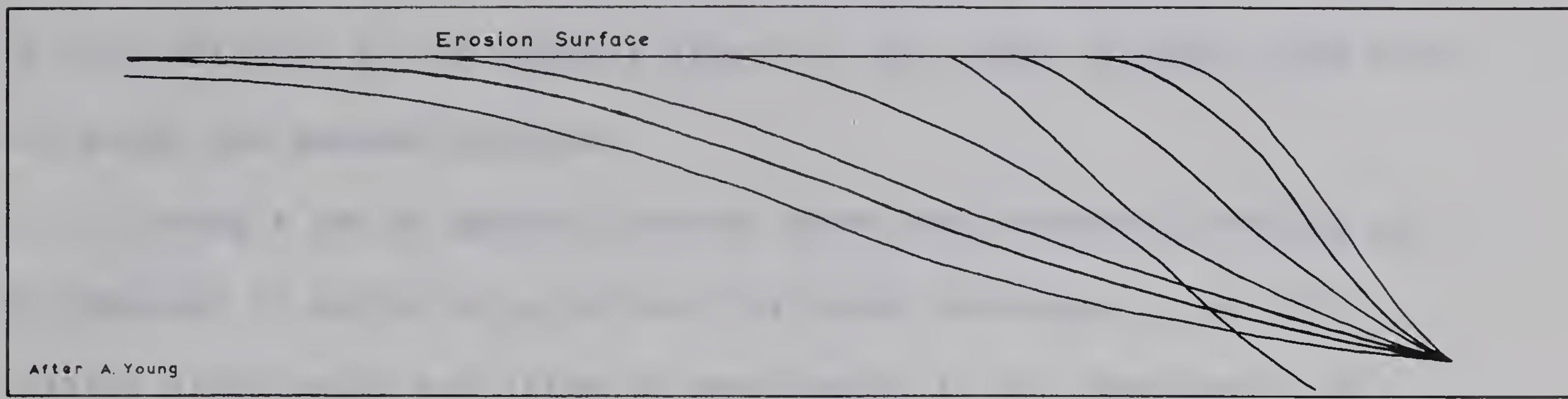

Figure 1: Superimposed Slope Profiles in the Heddon Basin, Exmoor, Devon, England.

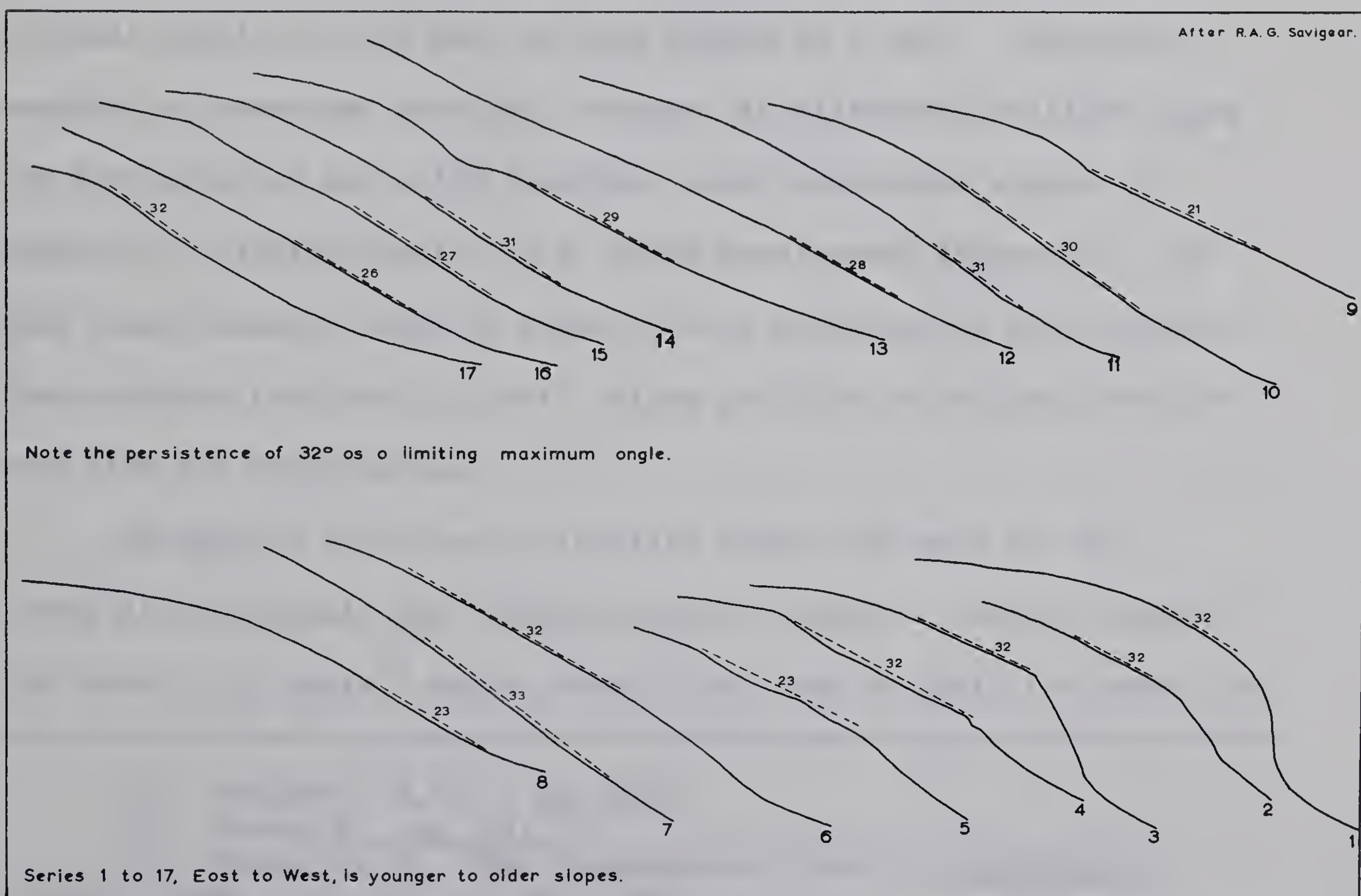

Figure 2: Successive Slope Development at Pendine, South Wales.

showed these slopes to be controlled by the bedrock surface, and that the regolith, while thickening and becoming more decomposed downslope, is thin relative to the overall sizes of the cross sections, and does not alter the general profile.

Young's use of graphic methods shows how measured profiles can be compared to arrive at a pattern for slope evolution. He also relates slope angle and stage of development to the development of regolith.

A similar approach to slope development was earlier followed by Savigear.[10] He examined a stretch of marine cliff which has been progressively shielded from wave action, and therefore from removal of basal debris, by the west to east growth of a spit. Graphical analysis of seventeen profiles, surveyed at different positions along the four miles of the cliff involved, shows successive stages of adaption to fluvial erosion, i.e. slope development (Figure 2). In this case, however, there is known to be a definite, if only relative, time sequence from west to east; slope profiles to the west have had more time for modification.

Savigear's selection of locality avoids the need for any assumption to explain the initial uplift or slope. Whereas Young,[11] like both W. M. Davis[12] and W. Penck[13] and some of their followers, had

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10 Savigear, R.A.G., op. cit..
11 Young, A., op. cit..
12 Davis, W. M., "The Geographical Cycle", Geographical Journal (1899), Vol. 14, pp. 481 - 504.
13 Penck, W., "Morphological Analysis of Landforms", Macmillan, (1953). A translation by Czech and Boswell of the 1927 edition published in German by A. Penck.

to assume rapid downcutting by some erosional agent, for Savigear the initial slope is provided by the marine origin of the cliff.

It is Savigear's observation of a known time sequence for compared profiles that supplied the technical approach to this study. Whereas Young assumed his profiles to be the equivalent to a sequence, with Savigear this is certain. The latter's profiles may not appear to be so smooth as Young's but the same general rule of upper parallel retreat leading to lower concavity appears valid.

Further definition to this thesis was provided by the work of Heusser.[14] He analysed pollen content from peat samples and was able to estimate dates of some events during the post-Wisconsin glacial history of the Canadian Rocky Mountains. At twelve glaciers Heusser dated the maximum Little Ice Age advance by dendrochronology (Figure 3). His method was to examine growth rings of trees that had been lifted and tilted by the ice advance: after tilting the rings grow unevenly. By counting the number of uneven rings the date of the advance can be calculated. Subsequent dates of recessional moraines were compiled by Heusser from earlier field recordings, aerial and ground surveys.

By determining absolute dates of recessional moraines, Heusser's work facilitates slope evolution studies on those moraines. At those glaciers visited in preparation for work on this thesis the recessional moraines reach a general maximum height and width of fifty feet and

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14 Heusser, C.J., op. cit..

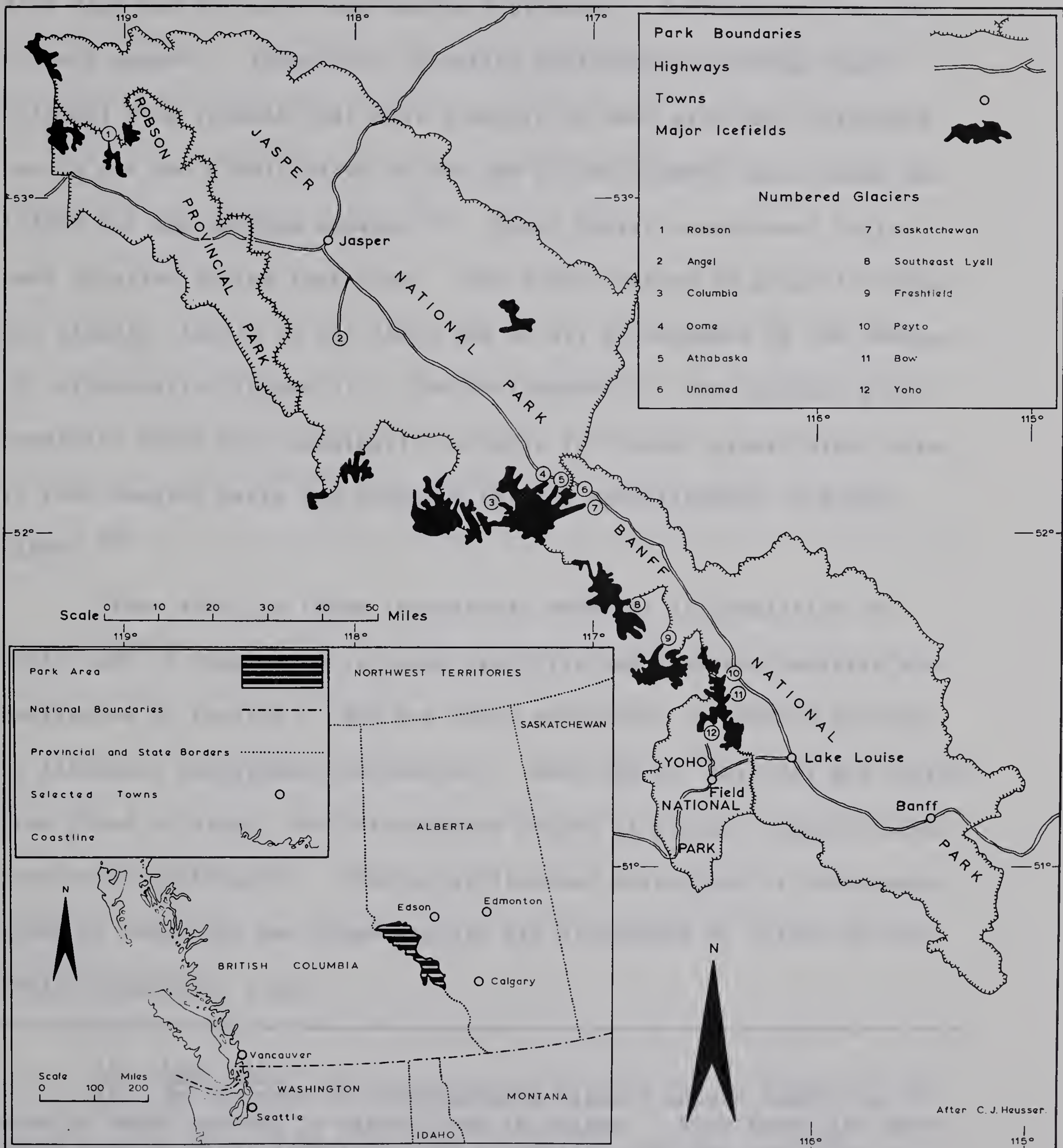
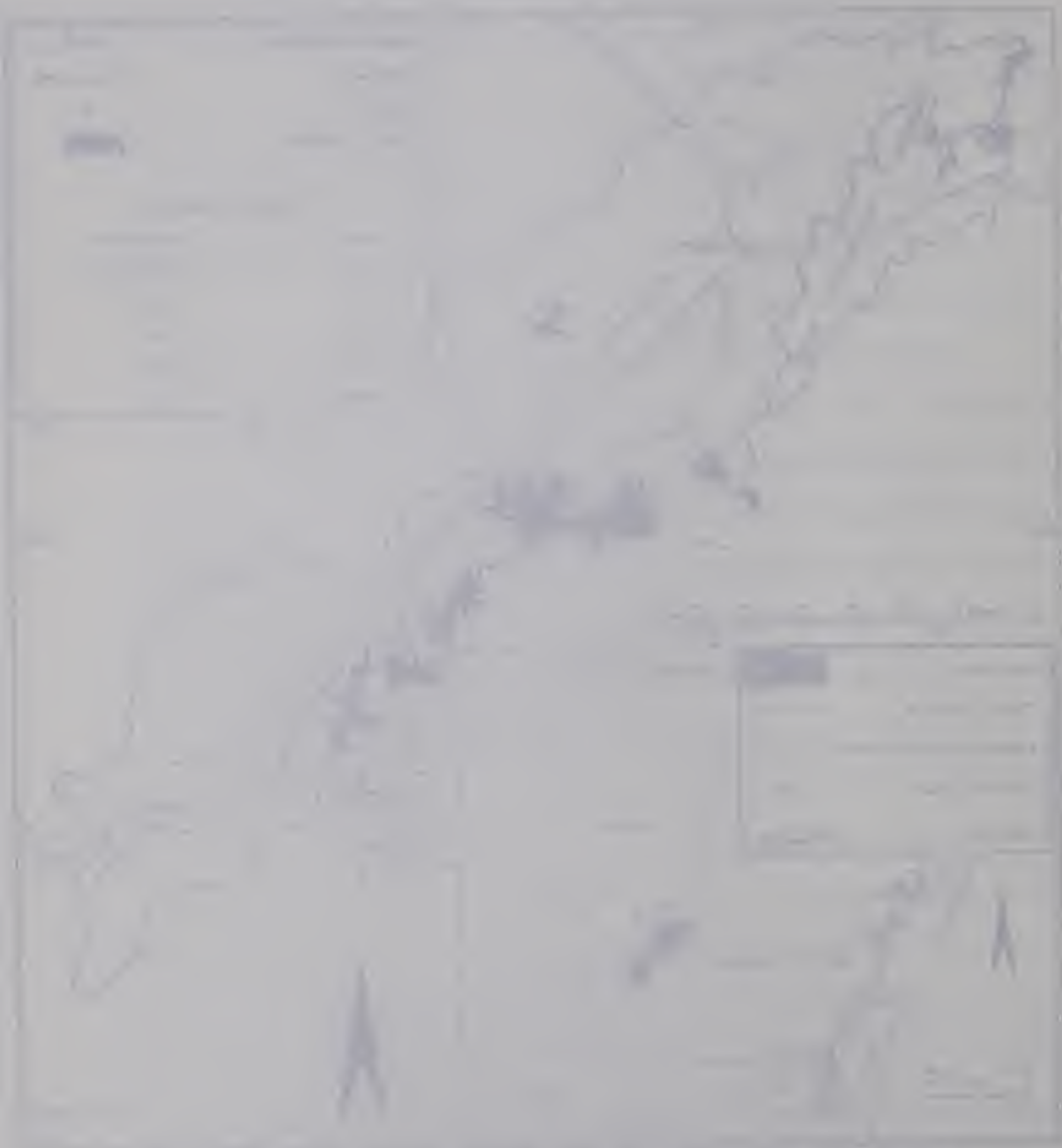


Figure 3: Glaciers of the Rocky Mountains of Canada.



two hundred feet respectively. More often the moraines are only a few feet high and not more than thirty feet wide. Furthermore they are closely spaced. Inspection of aerial photographs covering Jasper National Park reveals that most glaciers in that area have retreated one to one and a half miles in the one or two hundred years since the Little Ice Age maximum advance.[15] About thirty recessional halts have occurred during that time. The areas exposed by glacial retreat are clearly visible in the field and on air photographs by the absence of reforestation (Plate 1). The environment of the Canadian Rocky Mountains seems only marginally suitable for forest growth since three to four hundred years are required for the establishment of mature timber.[16]

Slope study on these recessional moraines is simplified by their lack of vegetation as slope stability and moisture capacity are unaffected by rooting. Nor are there variations of bedrock geology to influence topographic expression. Even though material may differ from place to place, the heterogenous nature of glacial deposits lends structural uniformity. Finally, altitudinal variations of environment along at least any one slope profile are eliminated by virtue of the small topographic scale.

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15 Loc. cit..

16 In the area of the Athabaska Glacier mature timber can be seen to reach seventy to eighty feet in height. Such trees are about three feet in basal diameter. At a campsite clearing two miles to the northeast of the Athabaska Glacier toe, tree stumps of three feet diameter reveal between three and four hundred tree rings.

With the chronology provided by Heusser, it became feasible to apply Savigear's and Young's approach to the study of slope development on successive recessional moraines. Despite the differences of scale, the method of comparison of measured profiles and their relationships to surficial materials is essentially the same.

Selection of the study area was limited to twelve glaciers for which Heusser had determined recessional history.[17] These glaciers are the Robson, Angel, Columbia, Dome, Athabaska, an un-named glacier, the Saskatchewan, Southeast Lyell, Freshfield, Peyto, Bow and Yoho (Figure 3). For each of these glaciers Heusser has dated the main recessional moraines and has related each to altitude and total distance of retreat.

When the most recent moraines are less than one year old, it is vital to watch their development during the first twelve months. To do this several visits are necessary, even though each may require less than a full day's work. Such visits also give some impression of the environment during all seasons. Good accessibility was therefore required in view of the harsh environment of the Canadian Rocky Mountains.

Of the twelve glaciers included in Heusser's work three are easily accessible, the Angel, Dome and Athabaska, and six of moderate accessibility, the Robson, the un-named glacier, the Saskatchewan, Peyto, Bow and Yoho glaciers. Easy accessibility means that the glacier can be reached quickly from the nearest highway.

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17 Heusser, C.J., op. cit..

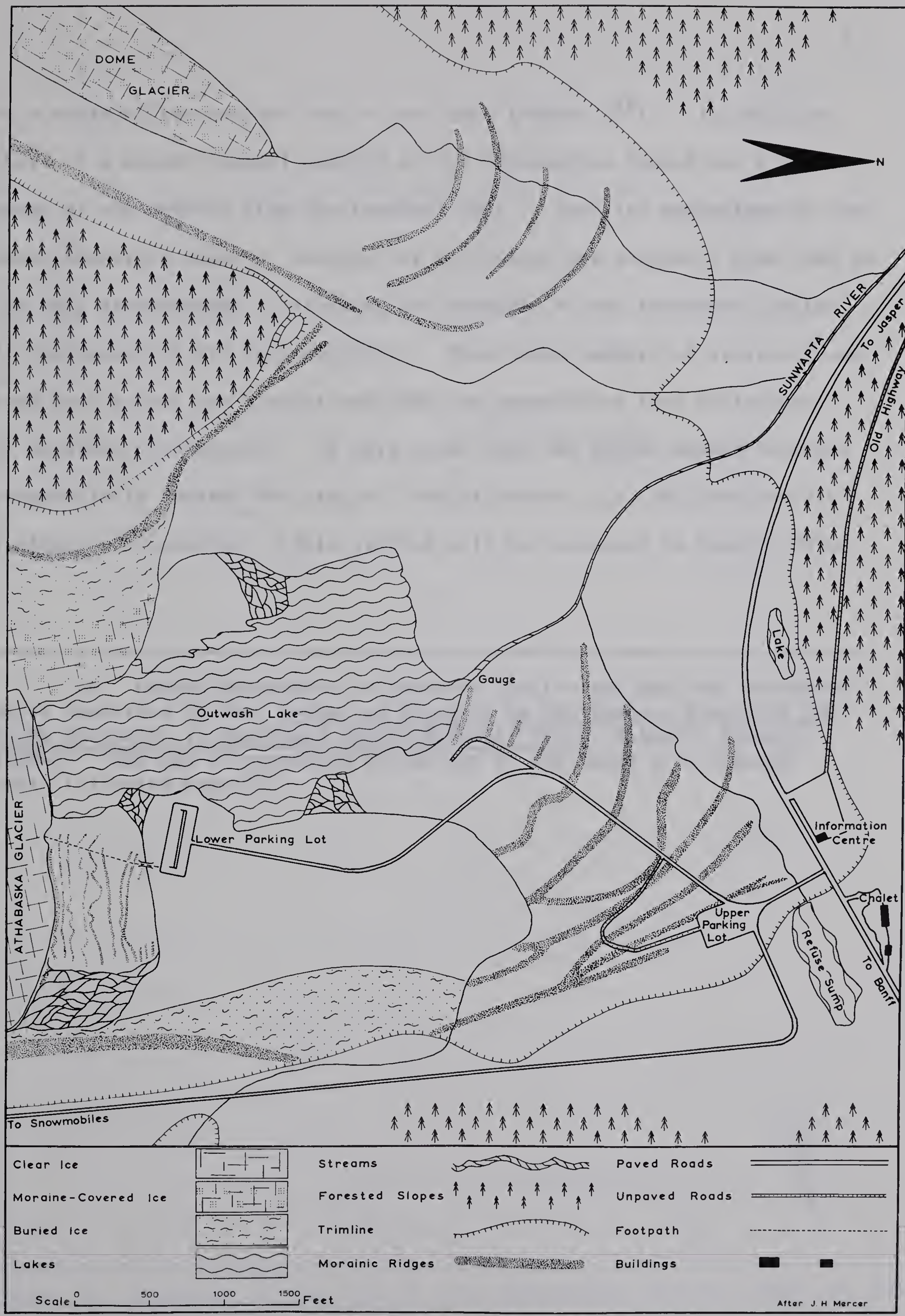

Figure 4: The Area of Study.

at a scale of two hundred feet to one inch (Figure 5[19]). In addition there is a meteorological station at the Information Centre and a stream gauge at the outflow from the terminal lake. Both are maintained by the Water Resources Branch; records for the latter are available from 1948 on. The only disadvantage in studying the moraines of the Athabaska Glacier is the result of its accessibility. Such large numbers of visitors come each year to see the glacier and ride the snowmobiles that disturbance of moraines is possible. If this is so then the effect should increase progressively towards the area of tourist access, i.e. the road and its footpath continuation. This problem will be discussed in Chapter Three.

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19 Canada Department of Northern Affairs and National Resources, Water Resources Branch, Survey of Glaciers on the Eastern Slopes of the Rocky Mountains in Banff and Jasper National Parks, Calgary, Alberta (1966). The map of recession of the toe is reprinted at a reduced scale following page 12.

CHAPTER II

LOCATION AND ENVIRONMENT

The Athabaska Glacier lies sixty-six miles by road southeast from Jasper; sixty-five by main highway plus a short distance on a paved access road (Figure 4 and Plates 1 to 3). To the northwest is the valley of the Sunwapta River and to the southeast the valley leading to Sunwapta Pass. Within five to three miles respectively either way from the Athabaska Glacier these valleys are about one third of a mile in width. At the Athabaska Glacier the Sunwapta Valley widens to over two-thirds of a mile across. At this point the valley is surrounded by Mt. Athabaska (11,452 feet above sea level and on the southeast side of the Athabaska Glacier), the Snow Dome (11,340 ft.a.s.l., between the Athabaska and Dome Glaciers), Mt. Kitchener (11,500 ft.a.s.l., west of the Dome Glacier) and Wilcox Peak (9,463 ft.a.s.l., north of the Jasper Highway). The floor of the basin lies between 5,700 feet and 6,000 feet above sea level.. Into this area flow the Athabaska and Dome Glaciers, two of the twenty or so glaciers issuing from the Columbia Icefields. During the Little Ice Age advance (1,000 A.D. to 1,750 A.D.) these two glaciers coalesced and covered the entire floor, but since then have retreated about one mile and now terminate at the margin of the main valley.

The trimline limit of the Little Ice Age advance is shown on Figure 4. Because retreat began sooner in some places than in others

the trimline does not represent contemporaneous dates of till deposition. The first known withdrawal took place in 1721.[1] Over the next two centuries the Athabaska Glacier retreated one-third of a mile. During this time several periods of mass-balance equilibrium occurred, resulting in concentrated deposition seen as large recessional moraines (Plates 1 and 14 to 17).

For the last fifty years retreat has been increasingly rapid and has covered two-thirds of a mile, a rate of three miles in two hundred years. During the last ten years the glacier has retreated one-fifth of a mile (equivalent to a rate of four miles in two hundred years). No major equilibrium periods have occurred during the last decade; deposits are mainly of ground moraine punctuated by small recessional moraines (Plate 4).

According to the nature of retreat and the overall slopes of the basin, the area in front of the Athabaska Glacier can be divided into three zones of different morainal characteristics. The first of these areas extends from the trimline to and including till of the early twentieth century. This terrain has no general slope but is characterized by large recessional moraines (Figure 6). These reach fifty feet in height and three hundred feet in width. The present sub-parallel patterns of the plan view are a result of even retreat of the glacier toe (Figure 4 and Plate 1).

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1 Heusser, C.J., "Post Glacial Environments in the Canadian Rocky Mountains." Ecological Monographs, No. 26, 1956, pp. 263 - 302.

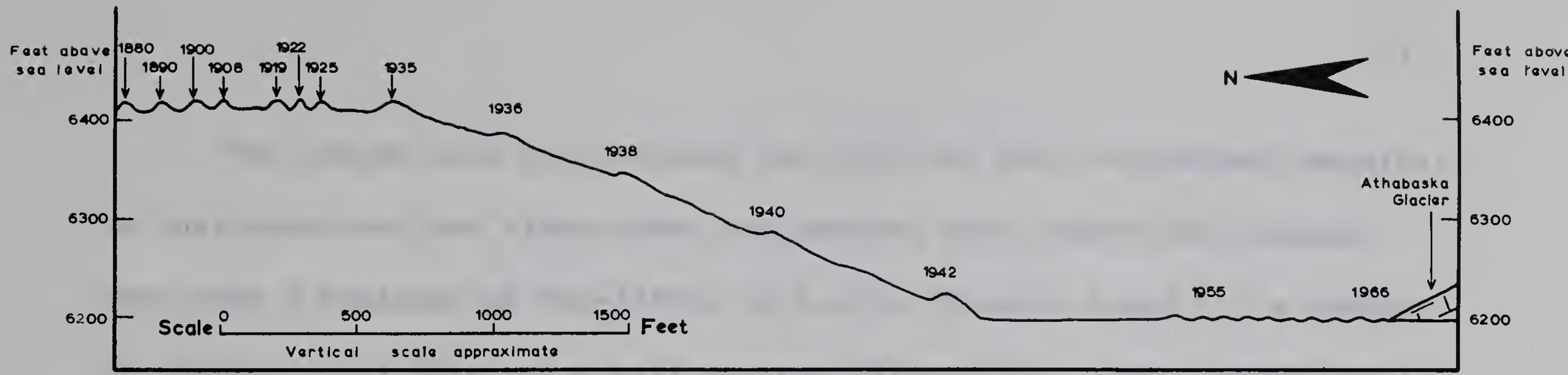

Figure 6: Sketch Section across the Moraines of the Athabaska Glacier.

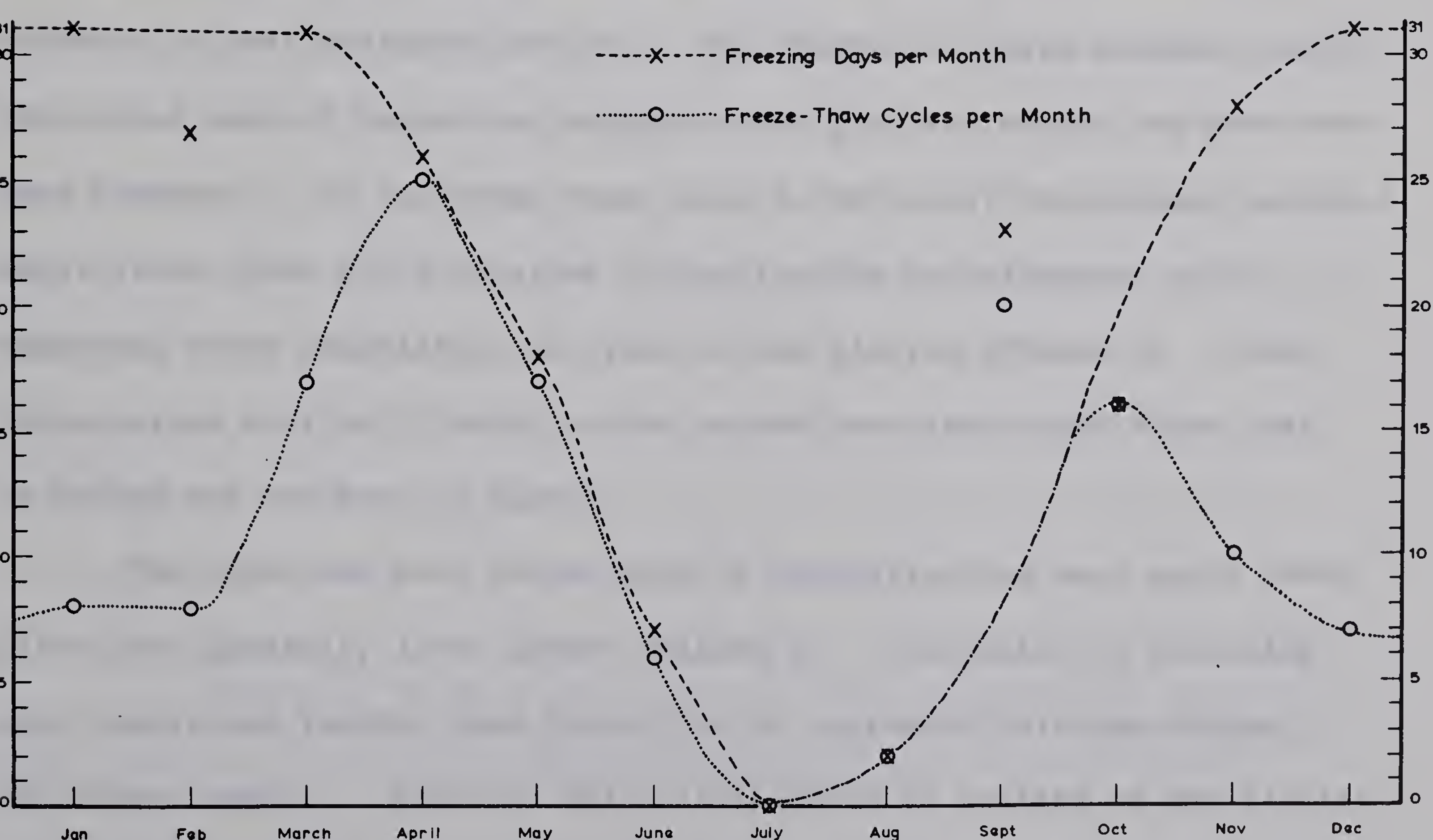

Figure 7: Freezing Days and Freeze-Thaw Activity, Jasper and Banff National Parks.

The second zone lies between the 1935 and 1942 recessional moraines. In this area the land slopes down two hundred feet toward the terminal lake over a distance of two-fifths of a mile (Figures 4 and 6), a gradient of approximately five and a half degrees (Plate 16). Here, recessional moraines are rarely preserved; instead signs of former outwash activity abound, e.g. small alluvial flats, dry channels, imbricate pebbles and stream-sorted debris.

Moraines as large as those of the nineteenth and early twentieth centuries are able to withstand the intensity of meltwater action that has and is taking place in front of the Athabaska Glacier. Although only fifteen to twenty feet high, the 1942 moraine still stands as a prominent, though somewhat isolated, feature, even though it is surrounded by evidence of past meltwater action. The absence of large moraines within the second zone of deposition suggests that glacier retreat was more even than formerly. On the other hand, only a few annual recessional moraines exist since these are more prone to destruction by meltwater, as is happening today immediately in front of the glacier (Figure 4). The few moraines that still exist in the second zone reach only three feet in height and ten feet in width.

The third and most recent zone of deposition has once again taken place over generally level ground (Figure 6). Recession is occurring more evenly and rapidly than before due to increased ablation during the summer months. Material which is released by melting of the glacier during the summer is "bulldozed" into a pile by forward movement of the glacier in winter. In this way piles of material, or annual recessional moraines, are created.

Much of this third zone has been modified by meltwater action, but in one part midway along the edge of the glacier a rise in the rock floor has preserved a series complete since 1956. It was on this site that most of the field-work was conducted (Figure 5).

Figure five shows recent readvance in places along the edge of the Athabaska Glacier. Fortunately, the area unaffected by meltwater action is also the one that has witnessed least readvance. Where such advance extends beyond an older moraine the latter would be expected to end abruptly against the more recent deposits. Field examination of the moraines at the Athabaska Glacier did not reveal this relationship. Consequently the accuracy of the details on the Water Resources Branch map (Figure 5)[2] must be doubted. The contradiction between map and moraines is possibly explained by the fact that toe positions are generally surveyed in May or June, at which time snow still covers the glacier. Instead of showing the actual toe the map illustrates the edge of the previous winter's snow cover. Since accumulation and spring melting rates vary each year the error would not be consistent. In the case of a winter with more than usual snowfall the toe would appear to have advanced. Plate five shows that in June, 1966, the "snow-edge" of the glacier was well in front of the 1965/66 moraine.

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2 Canada Department of Northern Affairs and National Resources, Water Resources Branch, Survey of Glaciers on the Eastern Slopes of the Rocky Mountains in Banff and Jasper National Parks, Calgary, Alberta, (1966), following p. 12.

No significant vegetation recovery has occurred since the early eighteenth century. Regeneration takes place first where the water table comes near to the surface. Because of the cold climate it seems that at least forty years pass before rocks decompose sufficiently for plants to become established. The first stage of regeneration in front of the Athabaska Glacier consists of alpine flora. The youngest trees in this area are growing on till deposited over one hundred years ago. Nowhere in the Rocky Mountains of Alberta has the author seen lichen as the usual first stage in a lithosere on morainal debris.[3]

Temperature and precipitation data are recorded at the Columbia Icefields Information Centre, but observations are made only during the summer months of some years. More continuous recordings are kept at Jasper, Cline Look-Out, the Upper Saskatchewan Research Station and Lake Louise (Figure 3 and Table I).

Nineteen sixty-five data are summarized here as they are the latest available at the time of writing and further represent the most complete set extant for the Columbia Icefields. For the five stations, January mean daily temperatures range between -5°F and 15°F: extremes are from -39°F to 48°F. In July the corresponding figures are from 50°F to 65°F and from 32°F to 88°F. Actual data for the Columbia Icefields are summarized in Table II. The Rocky Mountains of Alberta

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3 Stork, A., "Plant Immigration in Front of Retreating Glaciers, with examples from the Kebnekajse Area, Northern Sweden", Geografiska Annaler, Vol. XLV (1963), pp. 1 - 22.

Table I--Locations, Altitude and Available Data for Five Rocky Mountain Meteorological Stations[4]

Station	Latitude Longitude	Altitude Ft.a.s.l.	Available Data Type	Time
Cline Look-Out	52°10'N 116°41'W	6,000	T	May - Sept.
Columbia Icefields	52°14'N 111°27'W	6,000	T & P	June - Sept.
Jasper	52°53'N 118°04'W	3,480	T,P & W	Continuous
Lake Louise	51°25'N 116°10'W	5,032	T,P & W	Continuous
Upper Saskatchewan Research Station	52°11'N 116°27'W	4,260	T,P & W	Continuous

Temperature, Pressure and Winds are represented by their initials

belong to the Dcf classification of Köppen - a microthermal snow forest climate with no dry season, although the mountains cause noticeable local variations.

Freeze-thaw activity greatly modifies the morainal topography. Figure seven shows both freezing days and freeze-thaw cycles averaged from the available 1965 data at the five stations (Table I). If February freezing days, and September freezing days and freeze-thaw cycles are ignored, then smooth graph lines can be interpolated from the remaining points. The graph shows that freeze-thaw

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4 Canada Department of Transport, Meteorological Branch, Monthly Record Meteorological Observations in Canada. Editions are listed according to the month's data they contain. These take six months to prepare and publish.

Table II-- Summary of Meteorological Data Available for the Columbia Icefields[5]

Date	Temperature: Mean Maximum	Mean Minimum	Mean Daily	Difference from normal	Maximum	Date	Minimum	Date	Freezing days	Freeze-thaw cycles[7]
July 1961	59.7	38.9	49.3	-	69	13	28	1	3	-
Aug. 1961	61.4	40.6	51.0	-	72	4	32	7	2	-
Aug. 1963	59.9	38.0	49.0	-	-		31	22	2	-
Sept.1963[6]	-	-	-	-	67	8	-		-	-
June 1965	-	-	-	-	-		-		-	-
July 1965	61.2	39.3	50.3	-	72	26	32	13	1	1
Aug. 1965	61.3	41.4	51.4	-	78	2	27	29	4	4
Sept.1965	47.0	25.5	36.3	-	69	7	10	27	27	27

Date	Precipitation: Total Amount	Difference from normal	Days with more than 0.01"	Heaviest fall	Date	Snowfall (inches)	Days with measurable snow	Snow on ground at end of month (inches)
July 1961	3.36	-	12	0.90	16	0.0	0	-
Aug. 1961	1.95	-	9	0.80	16	0.0	0	-
Aug. 1963	1.36	-	8	0.49	12	0.0	0	-
Sept.1963[6]	-	-	-	0.27	13	-	-	-
June 1965	-	-	-	0.72	26	-	-	-
July 1965	1.93	-	12	0.39	11	0.0	0	0
Aug. 1965	1.04	-	15	0.64	25	17.5	7	0

No recording is indicated by a hyphen (-). Zero values are shown as such (0)

5 Loc. cit..

6 No records after September 15th of that year due to the official end of the summer season.

7 Freeze-thaw cycles were computed by the author from inspection of the daily maximum and minimum temperatures published by the Meteorological Branch (op. cit.).

activity is most frequent during spring and autumn, altogether about four months. Experience during the summer of 1966 indicates that the Columbia Icefields are always somewhat colder than the other stations due to altitudinal difference and local katabatic winds coming off the Icefield; the latter are particularly effective at night. These effects tend to shorten the summer season at the Columbia Icefields as compared with the other stations.

During June and early July of 1966, standing water froze each night only to melt again the next day. No further freeze-thaw activity was witnessed until the middle of August, and then only occasionally. Ground snow did not melt completely until late June. Even during July and August hail and sleet were common. Dry snow fell during a visit on October 8th, 1966, although none had accumulated. By January 1st 1967 snow had drifted in hollows to a depth of four feet: in many places it had been blown clear so that snow depth was only a few inches. The tops and windward (toward the glacier) slopes of most moraines were clear of snow, with accumulation taking place on lee slopes.

CHAPTER III

SLOPE MEASUREMENTS AND ANALYSIS

The end moraines of the Athabaska Glacier are of two size groups, small ones of a single winter's deposition and larger ones representing a concentration of deposits due to several years glacier standstill. Only one summer season of approximately three months was available for field-work. Survey of the larger moraines was therefore limited to measurement of the maximum segments of slopes (Figure 12). At twenty-three locations (Figure 8) several slopes values were measured using a Brunton compass. The locations were chosen where the moraines are straight so that curvature does not affect slope angle.[1] Measurements were recorded to the nearest degree, so that any one observation has a maximum possible instrument error of plus or minus one half of one degree. The error in interpreting the position of the maximum segment may be as much as two or three degrees. However, the Brunton compass measurements are analyzed only as averages of several observations (Appendix A), so that such large errors should cancel out.

For the smaller moraines, greater detail of topographic irregularities was obtained by the use of a steel rod three feet long and graduated every six inches, a twelve inch rule and an Abney level. Measurements were made where the moraines are straight and even in

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1 Van Burkalow, A., "Angle of Repose and Angle of Sliding Friction, an Experimental Study." Geol. Soc. Am. Bull., Vol. 56, (June 1945), pp. 669 - 708.

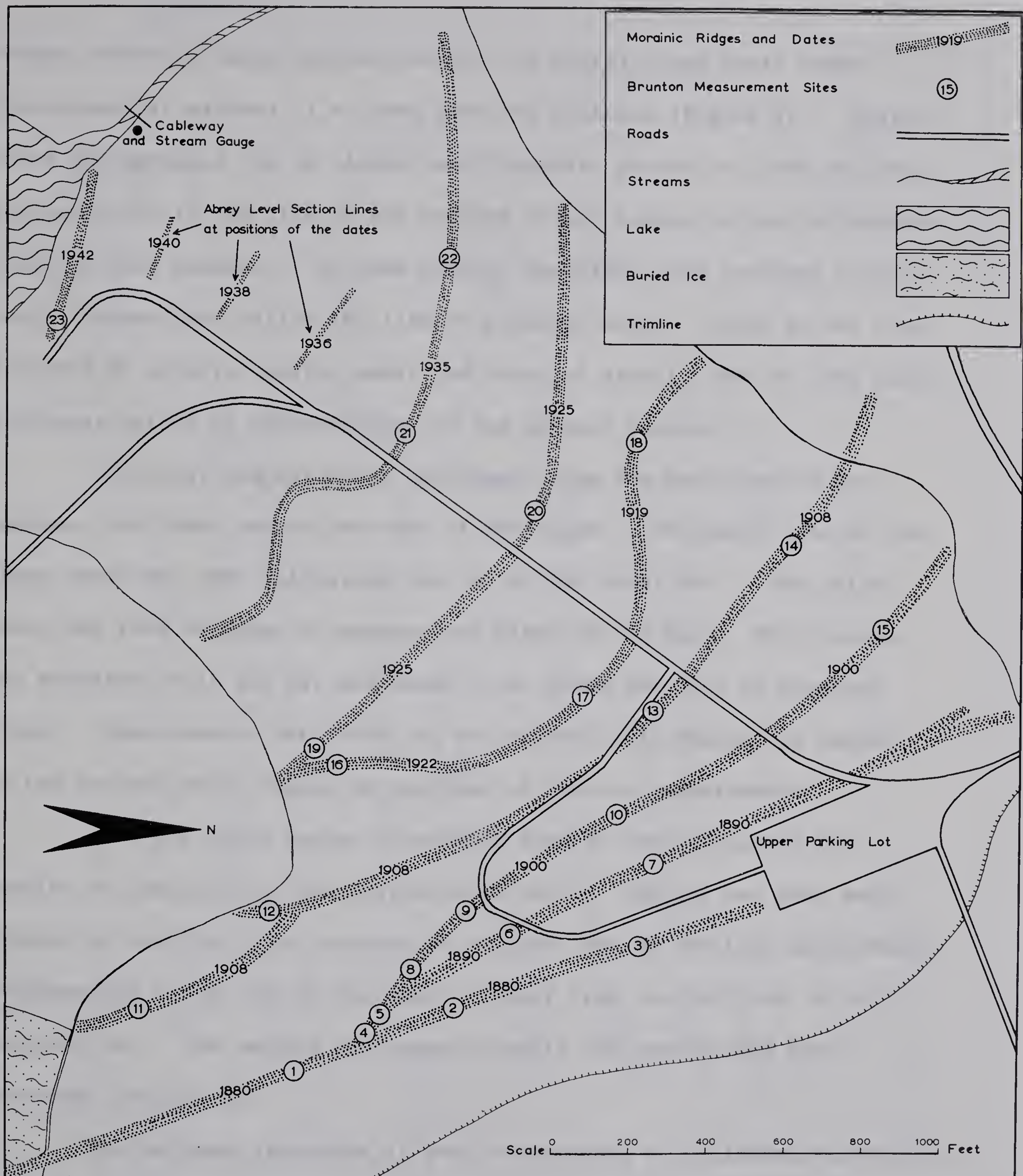

Figure 8: Locations of Till Samples, Brunton Compass measurements, and 1936 to 1940 Section Lines.

Till samples were collected from Brunton Compass measurement sites 3, 7, 10, 13, 17, 20, and 21, and from the positions of the dates on moraines 1936 to 1942 inclusive.

height, where no large boulders affect the profile, and where human disturbance is minimal, i.e. away from the footpath (Figure 9). Quite often the moraines lie on sloping and irregular ground, so that sections perpendicular to the line of the moraine do not always follow the greatest slope on that moraine. In some places, therefore, the sections turn so that as drawn they follow the line of greatest slope. This is the line followed by material moving under the force of gravity, one of the main processes active in the evolution of the moraine slopes.

The steel rod was first laid down along the back face of the moraine, its lower end at the foot of the slope. The sight tube of the Abney level was then laid along the top of the steel bar. The spirit level was then adjusted to measure the slope of the bar. This process was repeated until the bar was known to be along the line of greatest slope. Measurements were taken to the nearest half degree, as opposed to the nearest whole degree in the case of Brunton measurements.

At every three inches a vertical down to the surface of the moraine was measured to the nearest half inch. The bar was then moved forward so that the first reading of the next set of vertical measurements corresponded to, or was in the same vertical line, as the last of the previous set. The method was repeated until the moraine had been traversed (Figure 10).

The sections (Appendix A) were constructed by following essentially the same procedure. First, bar lines were drawn to scale, and at appropriate intervals the verticals were plotted. The point at the end of each vertical line is part of the constructed surface of that moraine.

Figure 9: Locations of Abney Level Section Lines, 1955/56 to 1965/66.

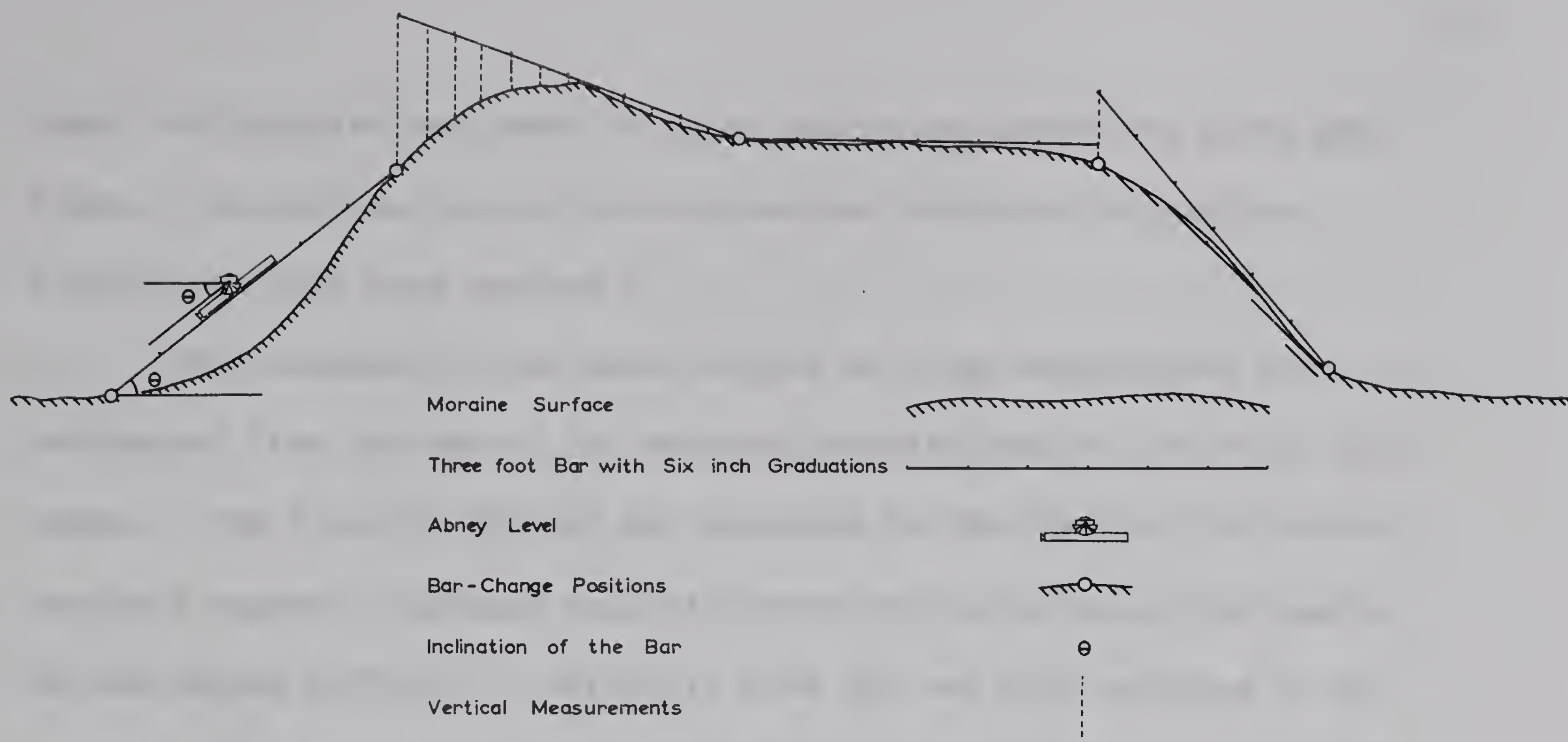

Figure 10: Method of Measuring Abney Level Section Lines.

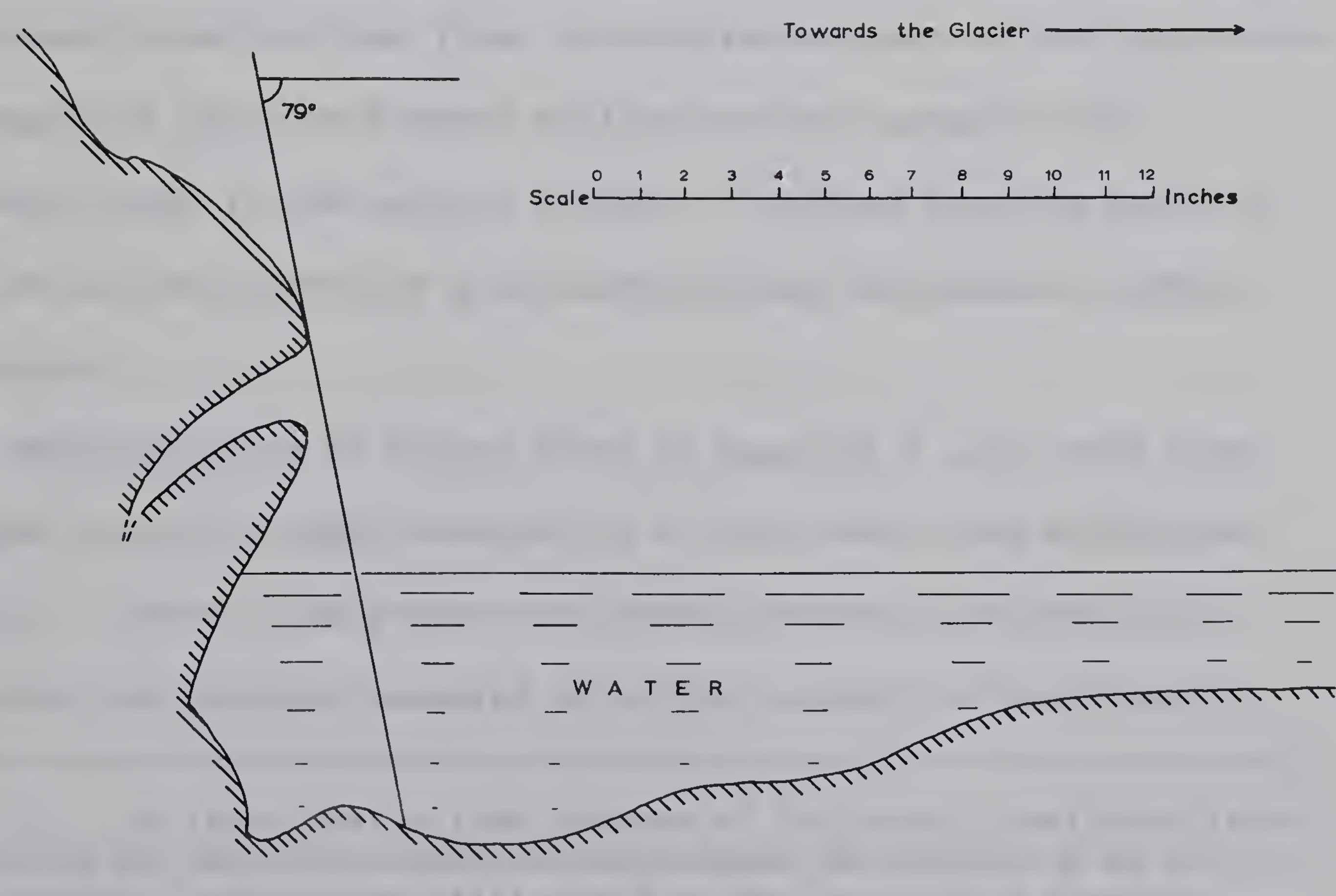

Figure 11: Overhang at Twelve and a Half Feet along the 1965/66 'B' Section Line, as observed in mid June.

Since the analysis was based on these points no connecting lines were drawn. In this way visual impressions and therefore subjective distortions have been avoided.[2]

The accuracy of the above method of slope measurement is determined from the sum of the maximum possible angular errors at each stage. The slope of the bar was measured in the field to the nearest one half degree, a maximum possible error of plus or minus one quarter of one degree ($\pm 0^{\circ}15'$). Verticals from the bar were recorded to the nearest half inch, a maximum error of plus or minus one quarter of an inch. Over the three feet length of steel bar this produces a maximum error of $\pm 0^{\circ}24'$. The bar angles were reconstructed by use of natural tangents. In this case errors are those of drawing and not of method. The sections were drawn on tracing paper over a backing of millemetre squared graph paper and the lines constructed as part of the hypotenuses of triangles of base one hundred millimetres and opposite side numerically equal to the natural tangent. Maximum possible error is plus or minus one quarter of a millimetre along the opposite side, or $\pm 0^{\circ}04'$ angle.

Maximum errors of slopes shown in Appendix A occur when they are at the shortest length measured, i.e. six inches (six millimetres to scale). These slope facets were drawn parallel to a series of plot points and tangents measured to within one half of a millimetre

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2 In order that a true picture of the detail available from the sections be obtained, these are reproduced in Appendix A at the same scale (one inch to one millimetre) as the manuscript drawings.

along the opposite side of a triangle of base six millimetres. This gives a maximum natural tangent error of plus or minus one quarter over six, an angle of $2^{\circ}24'$. The maximum possible error for a slope observation as shown in Appendix A is therefore $\pm\ 0^{\circ}15' \pm 0^{\circ}24' \pm 0^{\circ}04' \pm 2^{\circ}24'$, a total of $\pm\ 3^{\circ}07'$. However, for any slope greater than one degree angle and and six inches length this figure is reduced. For example a facet of three feet length and measured angle of thirty degrees will have a maximum possible error of $1^{\circ}06'$.

Processes.

The relationships of the geomorphic processes at work on the moraines, their causes, methods of operation, visible effects and some examples are shown in Table III. The 1965/66 moraine was first examined as the spring melt removed snow from and around the Athabaska Glacier (Plate 6). Most of the moraine was saturated by running or intersticial water, the remainder contained intersticial ice. All the geomorphic activity witnessed on the moraines was related to the melting and subsequent movement of ice.

Melting took place throughout June, at which time freeze-thaw was occurring daily. Some water evaporated from the surface so that one inch of dry till covered the body of the moraine. Occasional cracking (Table III) took place which, if over six inches deep, provided space for more water to enter from below and effect freeze-thaw activity.

Table III--Geomorphic Processes at Work on the Moraines of the Athabaska Glacier

Cause	Operation	Effect	Examples *
Seepage (infiltration)	Loss of support	Downward collapse	1965/66 B June-July, 8 - 12
		Settling	1965/66 E June-Aug, 3 - 4
Melting; Refreezing		Sliding en masse	1965/66 B 1 - 5½ 1965/66 C June, 3 1964/65 B 9 - 12½ 1962/63 B 0 - 3½
Drying (evaporation)		Sliding discrete	1965/66 C June-Aug, 1 - 2½ 1965/66 D June-Aug, 1 - 5½
Frost Action	Direct pushing at the surface (freeze-thaw)	Cracking and Overturning	1965/66 C June-July,10 1/3 & 11½ 1965/66 D June-Aug, 10 - 14
		Upward heaving	1965/66 A August, 9 1965/66 D July, 16 & Aug, 18
Surface Water	Washing	Removal of fine-grained rock material from surface	All moraines in general. Process actually witnessed over first few months of 1965/66 A - H.
		Runnels	1938
Wind Action	Deflation	Miniature dunes and deflation hollows	Outwash areas among 1925 to 1942 moraines.

* The examples are given in horizontal distances in feet from the start (zero) of the moraine as listed in Appendix A.

Alternatively, as intersticial ice began to melt, for some time it would refreeze nightly. This was also true of glacial meltwater, rain or melted snowfall of the previous morning or night. As a result, freeze-thaw activity took place on and in the 1965/66 moraine. These effects were only visible at the surface

and were most common on the steeper, less stable, faces (Table III and Plates 9 to 12).

As summer approached, meltwater was beginning to flow away rather than refreezing the following night. This process began in early June and occurred more frequently thereafter. Loss of intersticial ice led to a reduction of support and consequent collapse or gradual settling of the moraine. These processes were most common on less stable faces, particularly on the south side of the 1965/66 moraine. However, the most clearly visible example was the settling of the glaciofluvial sands, at a position three to four feet horizontally from the start of the 1965/66 moraine, section E, June to August (Appendix A).

Frost action and running water are most active on the newest moraine during the first melt season. After that period moraine surfaces stabilize through collapse and flattening of the steeper and less stable faces. Two or three years later these processes of stabilization become insignificant. On all moraines washing by melted snow and rain leads to the removal of finer particles from the surface. On some moraines rills are cut to a depth of one half inch and a width of two inches. After two or three years washing becomes the dominant geomorphic process, resulting in a general smoothing of moraine surfaces.

Topographic Forms.

The 1965/66 moraine was first measured when sections A to F (Figure 9) had been exposed to subaerial processes for at least one

month after deposition (Plates 8 to 10). The continuation toward the footpath emerged from beneath snow in the last week of June. Sections G to H were measured on July 16th (1966). For the period mid June to mid July, sections G and H of the 1965/66 moraine are recorded on Plates 5 and 6. Therefore, although the 1965/66 moraine sections A to F had already been measured in mid June and mid July, sections G and H of that moraine are the youngest sections available.

1965/66 Sections G and H.

The moraine at G and H is small but highly irregular in surface form (Plate 6). It consists of unsorted debris of maximum diameter four inches and contains a large amount of saturated silt and clay-sized material. There is no evidence of increasing human disturbance toward the footpath. This stretch of the 1965/66 moraine was surveyed at a time when much ice was melting, so that the morainic ridge and adjacent ground moraine (1965 and 1966 Summer deposits) were continually in a saturated state (Plate 7). The thermal capacity of the large amount of water on and within the deposits was sufficient to prevent the nightly freezing of intersticial water and subsequent frost-heaving. This water was also responsible both for some settling and for washing of finer particles from the exposed surfaces of stones.

1965/66 Section A (June to August).

The moraine proper lies between seven and thirteen feet horizontally from the start of the section line (Appendix A). It consists of unsorted debris, usually less than one and a half inches in diameter. Towards the glacier are deposits laid down during the

summer of 1966: away from the glacier are glaciofluvial materials (Plate 8). Melting, meltwater action and daily freeze-thaw activity caused much change by mid July, by which time collapse had occurred between ten and eleven feet horizontally along the section line, and the moraine had lost much of its surface roughness. By mid August frost action had pushed up a mound at the nine foot mark. This section is at the southeastern end of the moraine and is not representative of its slopes or full height, so that little can be said on slope development. It was measured for completeness in observing this particular stretch of the moraine. The 1965/66 A section line extends over ground holding much water and consisting in places of glaciofluvial material. Standing water favoured frost-heaving during July and August (Table III and Appendix A).

1965/66 Section B (June to August).

The moraine cross-profile starts at the three foot mark and is just over nine feet long. Materials are much the same throughout - a mixture of quartzitic sands and black limestone pebbles reaching a general maximum diameter of three inches. Topography is irregular, especially along the front face of seventy-nine degree slope (Plate 8). Slope measurements express only the slope between plotted points. In actuality there was an overhang at this point (Figure 11), but disturbance caused by measurement in June led to the collapse of this feature.

From mid June to mid July settling and collapse due to melting of intersticial ice occurred between eight and twelve feet horizontally from the start (zero) of the section line. The glaciofluvial material (1965/66 B June, between the zero and three foot marks) also collapsed. This

collapse allowed a hump of morainic material, situated in June between three and five point five feet along the section line, to slip down "en-masse" to between one and four feet from the start of the section line by mid July (Table III). Further collapse from mid July to mid August led to a steepening of slopes between one and six feet horizontally from the start of the section line. Frost heaving took place between the eleven and thirteen foot marks (Plates 11 and 12).

Although overall topography became more regular during the two month period, in certain places collapse and heaving led to the building of new forms and slopes. This was particularly true between the main moraine and the glacier.

1965/66 Section C (June to August).

This section is representative of the maximum dimensions of the short stretch of the 1965/66 moraine between sections A and F (Plate 8). The surveys reveal declining slopes and smoothing of the overall topographic form, particularly between the one and four foot marks. The materials are a mixture as described for 1965/66 Section B, except between zero and two feet from the start of the section, where twelve-inch rocks lie at the foot of the back slope. These cause the roughness at that point along the August survey line. The front face indentation at the ten foot mark along the June section line is a drying crack opened by frost heave. During the following month this and other cracks widened and led to overturning and general decline in slope angle (Plates 9 and 10). Another crack opened up at eleven point five feet along the 1965/66 July section line.

1965/66 Section D (June to August).

These sections are the best illustration of slope evolution by cracking and overturning. The June section shows three cracks, at ten point five, eleven point three, and twelve point three feet horizontally from the start of the line. Overturning led to talus development by July and two new cracks appeared at ten point seven and twelve point three feet along the section line (Plates 9 and 10). The slope was now more stable and development took place by sliding of the surface layer, so that by mid August the cracks were at eleven and twelve point five feet along the section. Mass slipping of about three cubic feet of debris was witnessed during the summer of 1966.

The back face of the 1965/66 moraine as shown in the D section line is unique in that only here was movement of individual particles observed. Materials here consist of sands and gravels (maximum diameter one quarter inch) that were characteristically dry during the summer of 1966. From mid July to mid August the foot of the backslope was under flowing water, so that basal removal and slope steepening took place.

Frost heaving occurred between fourteen and twenty-one feet along the 1965/66 D section line, where the material is of deposits from the summer of 1966. Mounds were created between June and July at sixteen feet and between June and August at eighteen feet horizontally from the start of the section line.

1965/66 Section E (June to August).

Similar frost action took place here as along the 1965/66 D section lines. 1965/66 section E illustrates flattening of slopes

which are initially unstable (seven to twelve feet horizontally from the start of the section line). Paradoxically, there is no change between the zero and two point five foot marks. The back face is dry at the base, whereas the front is saturated and seepage led to weakening and subsequent flattening. The area between two point five and seven feet along the section is of glaciofluvial sands which have settled producing a hollow on the moraine. Some collapse, probably due to the melting of intersticial ice, took place around the three foot mark of 1965/66 section E between mid July and mid August.

<u>1965/66 Section F (June to August)</u>.

The moraine extends from the eight point five to thirteen point five foot marks as measured horizontally from the start of the section line. Away from the glacier is a continuation of the glaciofluvial sands noted above. Towards the glacier are summer deposits showing both settling and frost-heaving. These processes led to modification of the moraine itself, for example, collapse and steepening on the front face and then a return to the initial slope value.

<u>Summary of Development during the First Year</u>.

Although not surveyed in chronological order, the sections 1965/66 G and H and 1965/66 A to F (June, July and August) provide a record of moraine evolution during the first three months of periglacial exposure. At the start the morainic ridge was a loose mixture of debris. Localized settling and frost-heaving caused some steepening. In general, however, the processes outlined in Table III were responsible for initially rapid slope flattening and smoothing of overall topographic form.

Further visits to the moraines of the Athabaska Glacier were made on October 8th 1966 and January 1st 1967. By October the 1965/66 moraine had not changed substantially compared to the rate at which changes were previously taking place, although some smoothing of surface detail had occurred. At that time there were patches of loose snow. There had been occasional snowfall since August but each time it had melted within two or three days. By January 1967 most of the area was under snow drifts, but the tops and front faces (windward) of the moraines were visible. No further slope development was taking place since the till was frozen. The top one foot of the front face of 1965/66 C to E section lines measured 35^{o} to 40^{o} by visual estimation; the remainder was buried by snow.

1964/65 Sections A to D.

There are no progressive changes in slope angle toward the footpath as a result of human disturbance. The size difference along the 1964/65 moraine as shown in sections C and D (Plate 13), compared to sections A and B of the same moraine, is too great to be the result of disturbance by man. The size difference reflects variations in the amount of deposition. Sections 1964/65 A to D illustrate progressive smoothing, particularly of the front face (compare with the 1965/66 moraine, section line D as measured from June through to August). Irregularities on the 1964/65 moraine, section A, at horizontal distances of one point five feet, three point five to six feet, and eleven to thirteen feet from the start of the section line, are caused by an increase in rock size to twelve inches. There is an

expectable tendency for larger stones to settle at the slope foot. Individual boulders cause some surface roughness at one foot and three point five feet horizontally from the start of section 1964/65 B. Between nine and twelve feet along the same section, "en-masse" slipping of the upper three inches of debris had taken place.

1963/64 Sections A to D.

As above there is no evidence of increasing disturbance toward the footpath. The seventy-one degree slope at four point five to five feet along section A is the surface of a twelve inch boulder. At the time of measurement this moraine was two years old and there were few cracks or collapse features. The till appears to be becoming less susceptible to the effects of the stronger processes of frost and gravity. The more gradual processes of snowmelt, stream and rainwash action are becoming dominant.

1962/63 Sections A to C.

Between four point five and six feet along section A, three and four feet along section B and nine and eleven feet along sections A, B and C, twenty inch boulders cause major irregularities. The remainder of the 1962/63 moraine is of till containing stones with a maximum diameter of three inches. Other than the large boulders mentioned above, the topography of this moraine is similar to that of the 1963/64 and 1961/62 moraines. Although the overall form of 1962/63 section C is smoother than 1962/63 section lines A and B, the thirty-four degree back face and thirty degree front face on section C indicate that at least parts of that section line are no more

disturbed than sections A or B. In other words there is no apparent change of slope along the moraine towards the footpath. Between zero and three point five feet horizontally from the start of 1962/63 section B is another example of "en-masse" slipping, a rare occurrence on moraines over two years old.

1961/62 Sections A to C.

These sections show general consistency of main slopes in the thirty to thirty-eight degree range. The slope break in 1961/62 section B at the one point five foot mark corresponds to a twelve inch rock. Elsewhere, the materials are mainly of sands but intermixed with stones reaching a maximum diameter of two inches. Despite this homogeneity, slopes are not necessarily uniform, showing that slope flattening does not occur everywhere at the same rate. In this case a thirty-two degree slope passes upwards into one of forty-eight degrees. This may be a reflection of the discrete processes, such as collapse or frost-heaving (Table III), which are at their strongest during the two or three years after deposition of the moraine.

1960/61 Sections A to C and 1959/60 Sections A and B.

None of these five sections has facets steeper than thirty-eight degrees (for example between seven and eight feet along 1960/61 section A). 1960/61 section C is on ground rising away from the glacier, hence the asymmetry. Both 1960/61 and 1959/60 sections A illustrate the tendency for larger rocks to fall to the base of the slopes. The foot of the back face of 1959/60 section A has eight inch rocks. As on other sections, some irregularities are merely

the result of large boulders set within the moraine, such as between six and eight feet along 1959/60 section B, and between the three and three point five foot marks of 1964/65 section B.

1958/59 Sections A to D.

Sections A and C compared to B and D illustrate the size range that can be found over short distances along annual recessional moraines (see also 1964/65 sections A to D). At the northwest end of the 1958/59 moraine, the ground slopes down toward the glacier, causing the asymmetry of section D. Between seven and eight feet along section A of 1958/59, from the four to the five foot marks of section B and between six and seven point five feet along section C, increases in surface roughness correspond to debris as much as twelve inches in diameter. Elsewhere the maximum size is four inches. Where the moraine is relatively smooth the maximum size of debris is between one and a half to two inches diameter.

1957/58 Sections A and B, 1956/57 Section A and 1955/56 Section A.

Only small stretches of these moraines are left (Figure 9), indicating that the central portions have possibly been disburbed by man. At present the snowmobile tours run from the lateral moraine on the southeast side of the glacier, about one mile from the toe (Figure 4). Before 1960 they were based at the foot of the glacier. Two footpaths are still visible between the footbridge and the disturbed area which used to be the starting point for the snowmobiles. Because of the increased probability of human disturbance in the immediate surroundings, it would be unsafe to trust slope readings

without comparing them to areas where less disturbance has occurred (i.e. the more recent moraines). However, their slope values and topographic forms are consistent with those on younger moraines and are presented here to complete the picture of moraine evolution within the area bounded by the Athabaska Glacier, terminal lake, and meltwater stream (Figure 9).

For most of the 1957/58 moraine the maximum size of materials is three inches in diameter, but at zero to one point five feet horizontally along 1957/58 section B, some debris is six inches in diameter. Some slopes of forty degrees persist, for example at seven point five to nine point five feet along 1958/59 section C and between two point five and three feet along 1957/58 section A, but slopes longer than two feet rarely exceed thirty degrees. The same is true of slopes on the 1956/57 and 1955/56 moraines. Between the 1956/57 seven point five to eight point five foot marks, and from one point five to three feet along the 1955/56 section, materials attain sizes of six inches in diameter.

Summary of Moraine Evolution over Eleven Years.

For the first four years topographic changes are rapid due to the ease with which the processes outlined in Table III can act on the poorly compacted deposits. As settling and compaction take place slope development becomes slower. The ice within the moraines melts and the moraines dry out, reducing the actions of frost and running water. Since surface wash from precipitation continues it becomes relatively more important.

Initial slopes and forms show great variations and irregularities. Maximum slopes are progressively reduced except where boulders larger than twelve inches diameter appear at the surface. For the eleven year period covered, facets of forty degrees are maintained, but these are rarely found to be longer than two feet.

There is a tendency toward straight slopes, although on some smaller moraines thirty degree slopes merge with short sections of forty degrees and result in concavities, followed by relatively small summit convexities. Some larger moraine profiles show a tendency to convexity, with maximum slopes at the base being in the thirty to thirty-five degree range.

Moraines Dating from 1873 to 1942.

Average slopes for the period 1955 to 1966 are approximately twenty-five degrees. For 1873 to 1942 slope values are mostly between twenty-seven and twenty-nine degrees. However, the 1955 to 1966 average includes summit convexities and ledges on the flanks of the moraine. Furthermore, slopes on the sections measured by Abney level traverse refer to generalizations for a given length of moraine surface, whereas Brunton compass measurements are of the slope at the points of inflexion (the steepest point) of the moraine surfaces. It is difficult in the field to assess objectively where a continuously curving slope begins and ends. On the other hand, the Abney sections are of relatively small moraines and reveal surface irregularities which make it impossible to identify exactly the location of the steepest slope segment. Brunton compass measurements, therefore tend

to give higher values with respect to those taken from the Abney level section lines (Figure 12).

The 1936, 1938 and 1940 moraines were measured by Abney traverse and were found to have main slopes between twenty-four and twenty-eight degrees. These values agree closely with the more recent moraines. This reflects, if only circumstancially, the consistency of the method and accuracy of measurement.

Altogether, twenty-five moraine dates were surveyed. The four most recent (1965/66 June to August and 1964/65) have exceptionally uneven profiles due to the recency of deposition. The moraines 1940 to 1936 are also exceptional in the sense that the system of measurement applied to them varies from that applied to adjacent moraines (i.e. Abney traverse instead of Brunton compass). Of the remaining eighteen sets of data, only three (1962/63, 1960/61 and 1955/56) do not follow a general trend of slope decline to stable facets between twenty-five and thirty degrees.

Most of the moraines dated between 1873 and 1942 exhibit smoothly curving slope profiles (Figure 12 and Plates 14 to 17). Some smaller moraines show upper concavity, for example the 1880 moraine in the vicinity of Brunton measurement at site number three (Figure 8). Materials are of sandstones and quartzites, as compared to mainly limestone in more recent deposits. The older till is of relatively rounded sands and gravels (Chapter 4), probably outwash deposits of post-Wisconsin age which were reworked by the Little Ice Age advance. The maximum size of this material is generally six inches, but there is

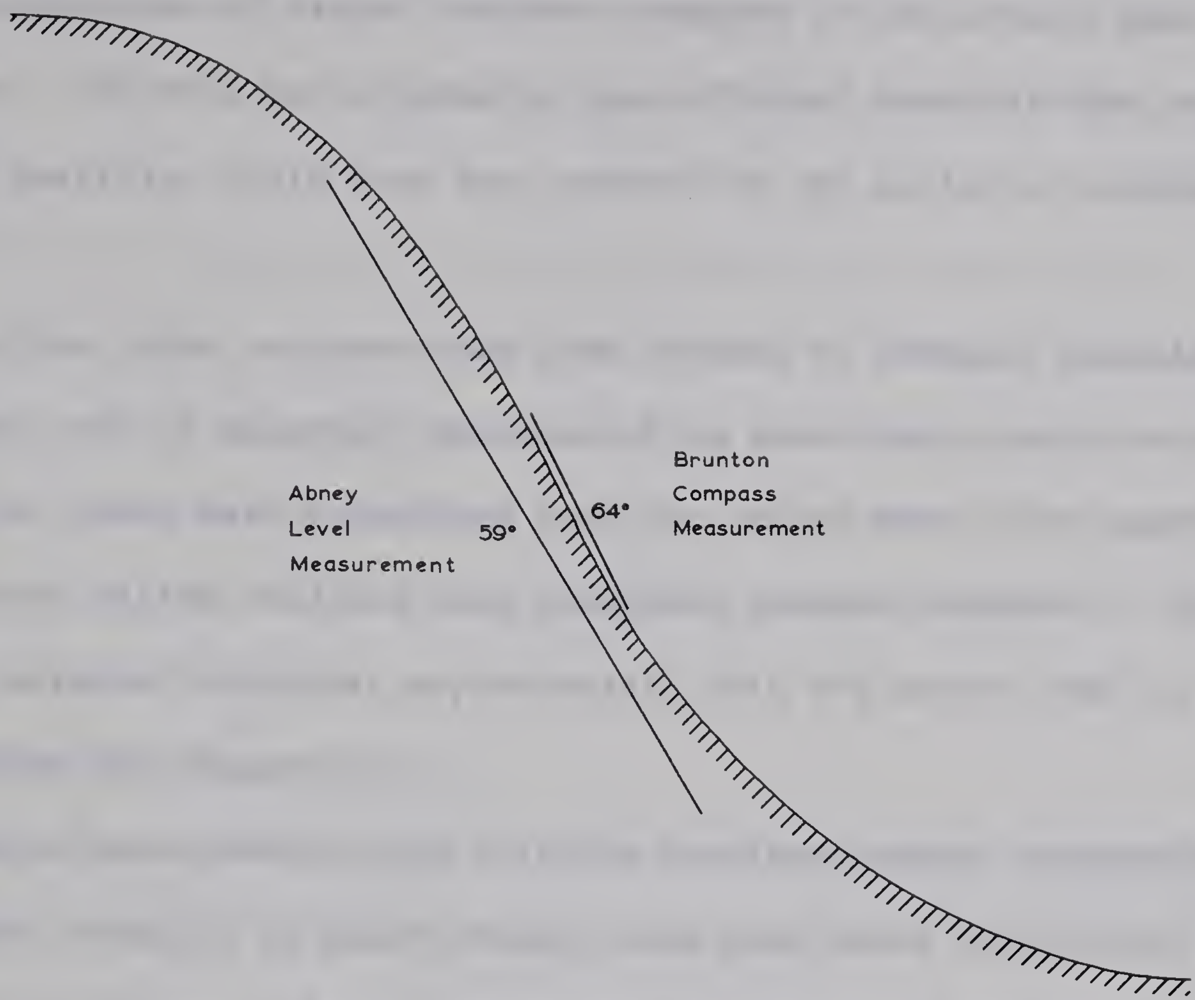


Figure 12: Characteristics of Brunton Compass and Abney Level Slope Measurements.

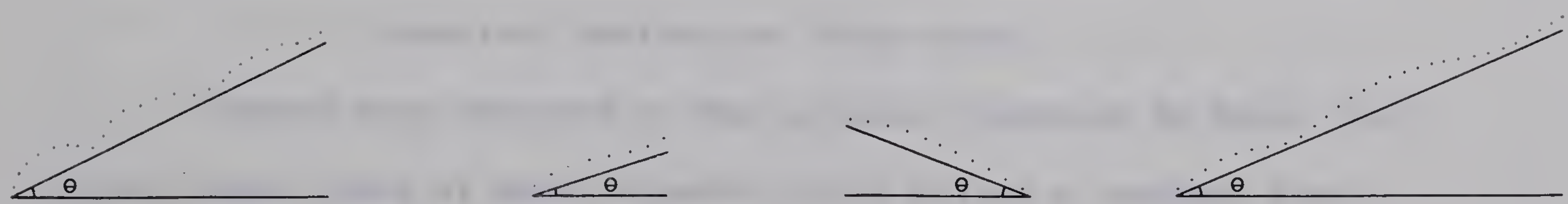


Figure 13: Measurement of Facets on Sections Measured by Abney Level Traverse.

a higher proportion of larger boulders compared to the area of more recent deposition. If this was originally glaciofluvial material then many of the finer particles would have been removed by the action of running water.

As the older moraines turn from lateral to terminal positions the general size of materials decreases from sands and gravels to mainly sands. The sands were introduced from the valley side; the gravels come from the valley head and have undergone greater abrasion. This change of material coincides approximately with the access road to the Lower Parking Lot (Figure 4).

Slope measurements show that the moraines undergo progressive change from irregular to smooth forms, with main faces stabilizing at twenty-eight degrees. Evolution is most rapid during the first three or four years, and is related to the number and intensity of operative processes. During this early stage the till is loosely compacted and irregular in topographic form. Periglacial processes can work quickly to create slopes of twenty-five to thirty degrees which are presumably close to or near the angle of rest of the material.

Numerical Analysis of Slope Data

Facets were measured on the sections traversed by Abney level survey where three or more adjacent points lie on a straight line. Where deviations of lines joining adjacent points are reversed over two

or three points, or where cumulative deviations are less than three millimetres (three inches to scale), longer facets were measured (Figure 13).

The above facets and the Brunton compass measurements are contained in Appendix B. Slope values are plotted left to right and increasingly older dates of moraines from top to bottom. At each intersection is shown the number of measured occurrences of that slope angle on that moraine. Appendix B also includes other information as explained in the headings.

Range, Centrality and Upper Limit.

The tabular presentation of Appendix B reveals a trend toward concentration of slope values between twenty and thirty degrees. Range is the difference between lowest and highest slope value recorded for any given moraine. Central value refers to the centre of the range as defined above, and the upper limit is the highest slope value on that moraine. Ranges, central values and upper limits are listed for each year in Appendix B and are plotted on Figures 14, 15 and 16. Although the ranges of values (Figure 14a) have a wide distribution, this is small compared to the overall size of the graph (i.e. the maximum possible distribution). Furthermore, a distinct trend is indicated by the limiting and median guide lines. For the first fifty years, slope value ranges decrease from seventy-nine to between ten and twenty degrees. Not only do these ranges decrease, but for the first ten years (Figure 15a) so also do the central values.

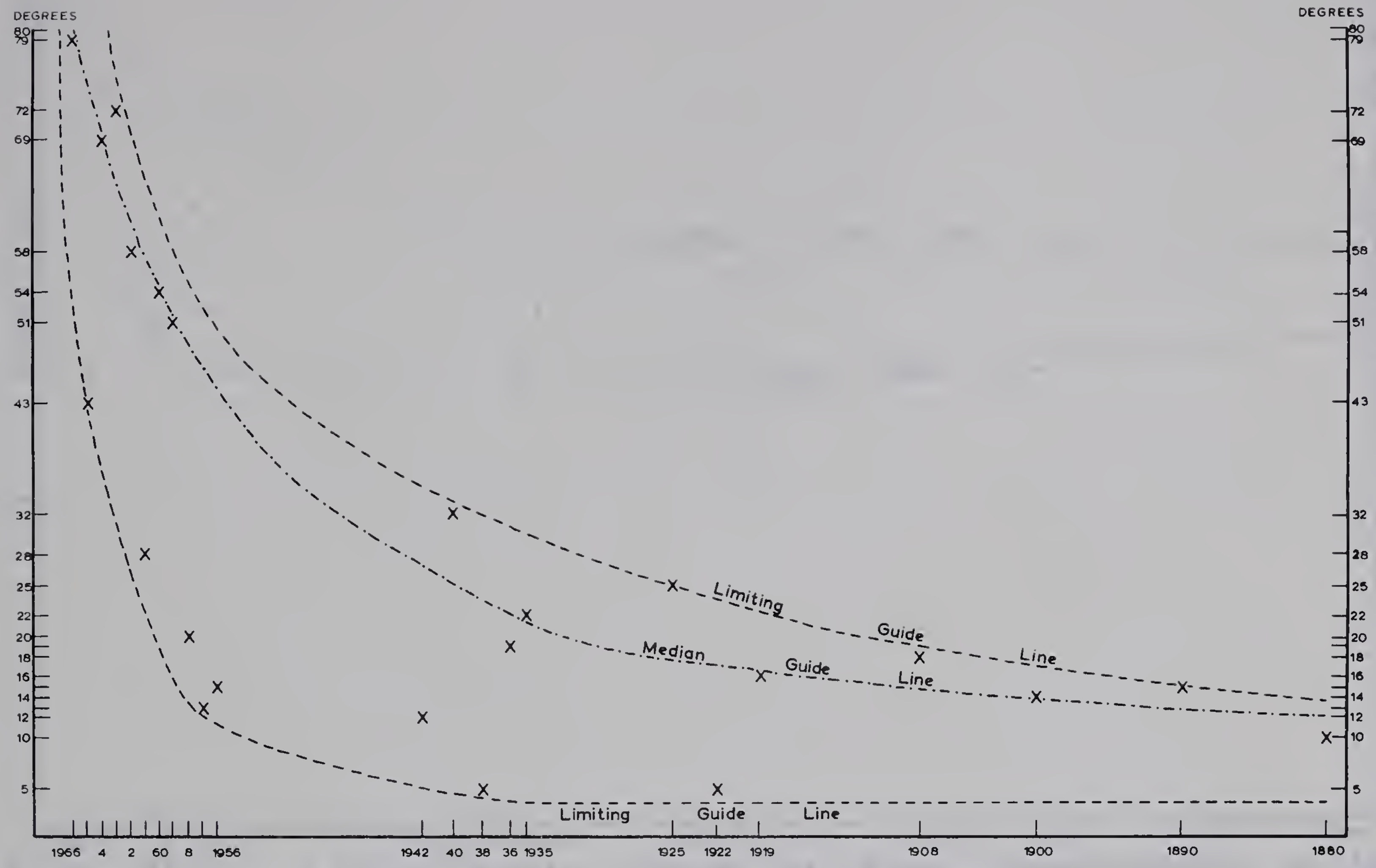


Figure 14 (a): Actual Ranges of Slope Values on the Moraines of the Athabaska Glacier.

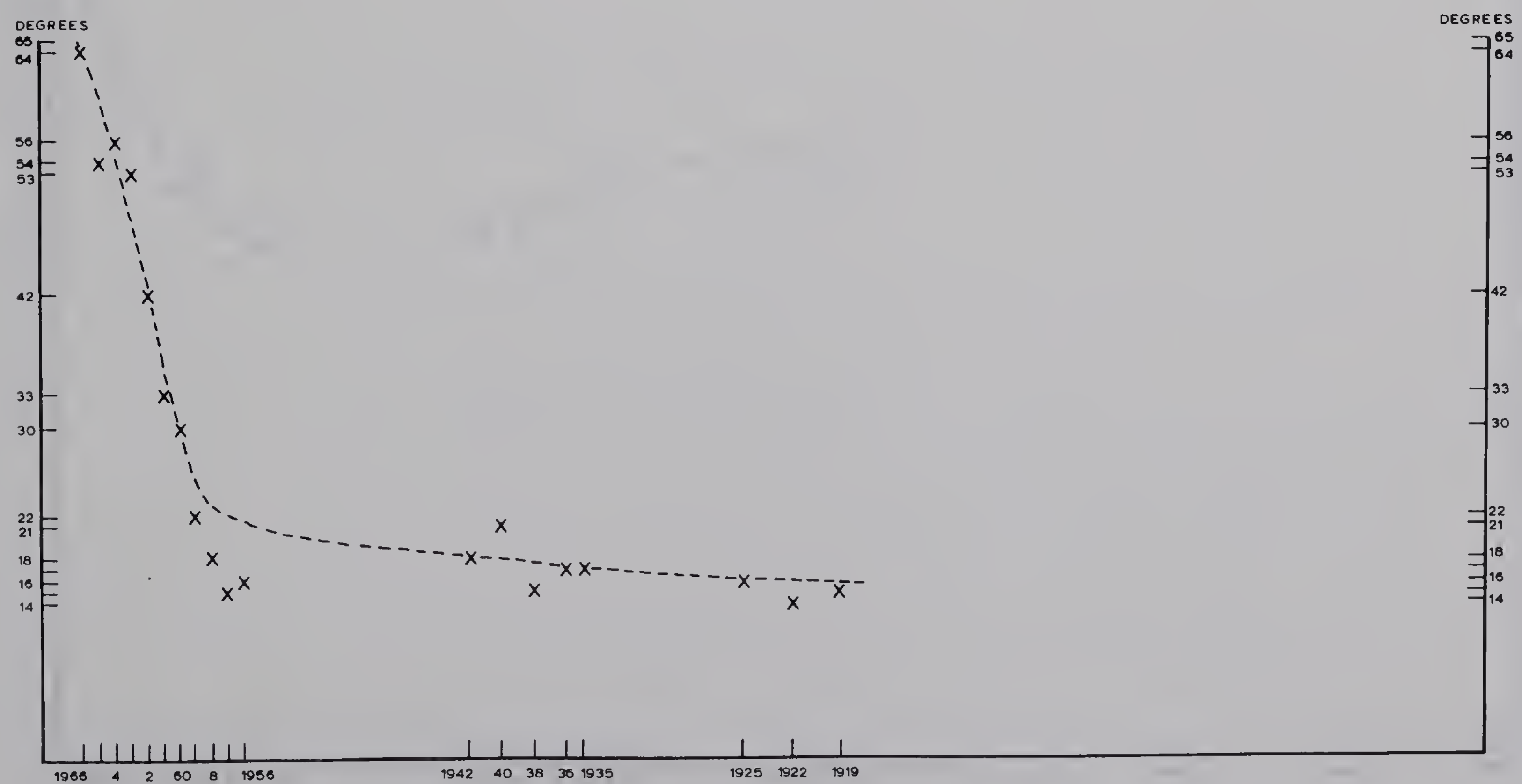
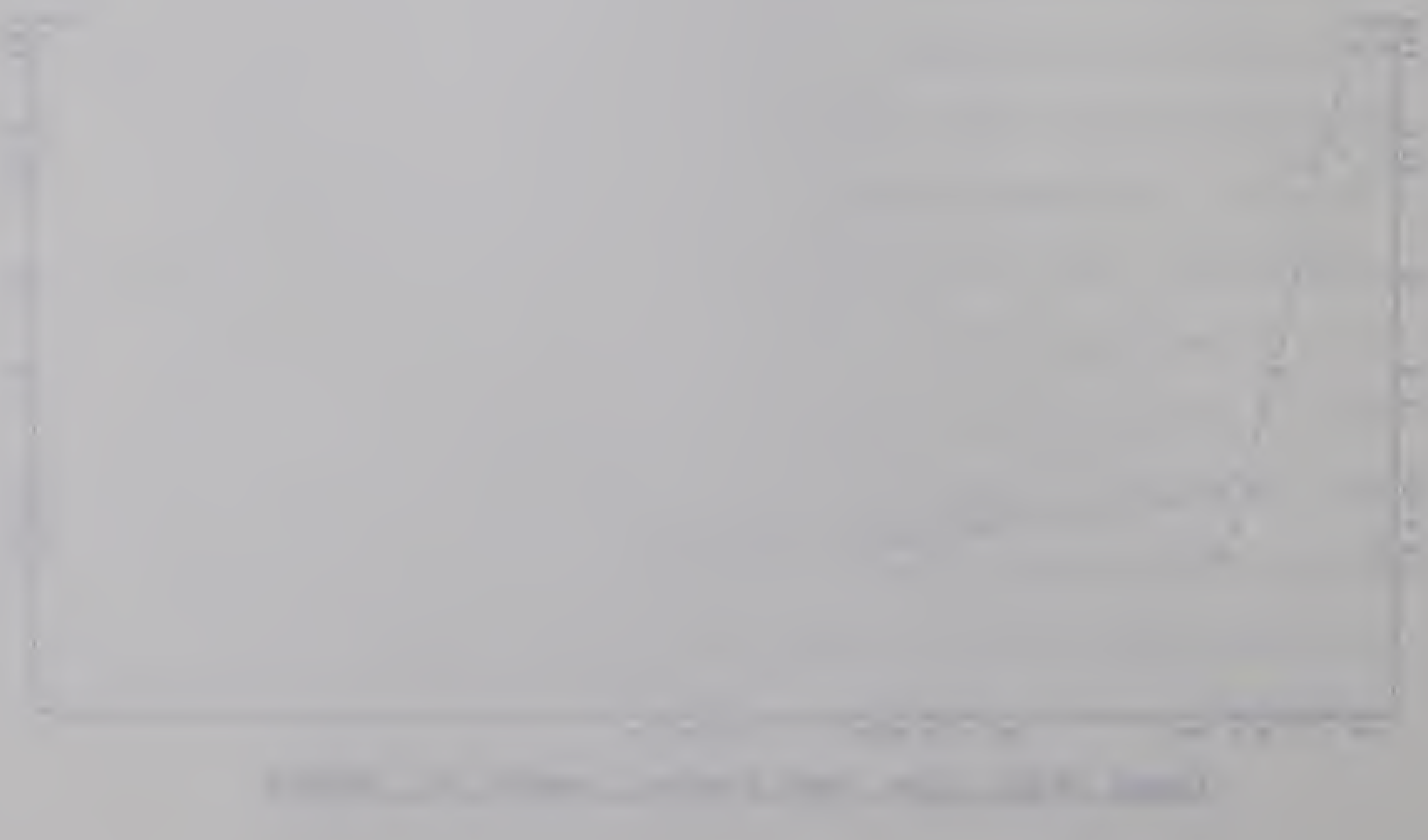


Figure 14 (b): Five Year Running Means of Ranges.



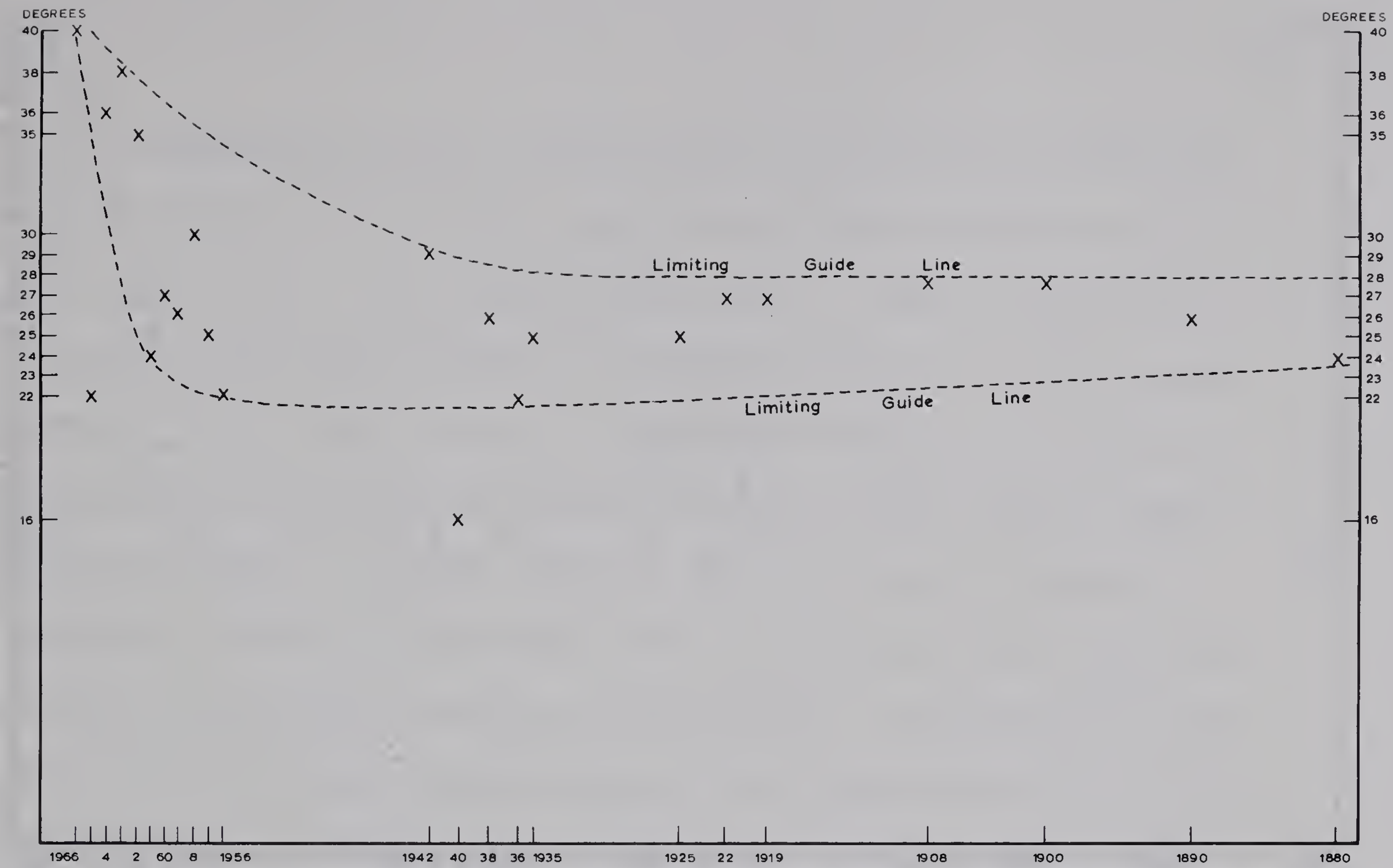


Figure 15 (a): Actual Central Values of Slope Measurements on the Moraines of the Athabaska Glacier.

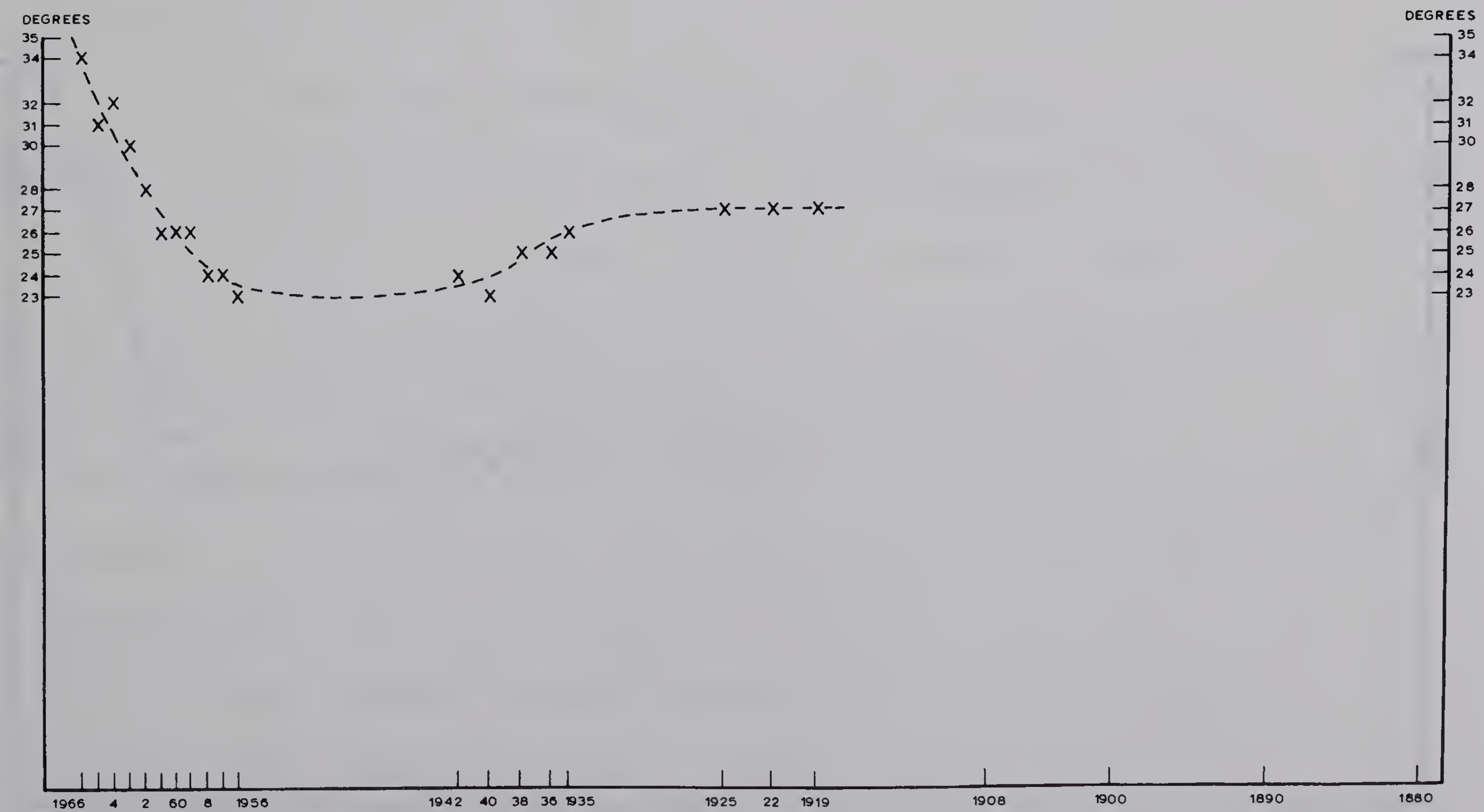
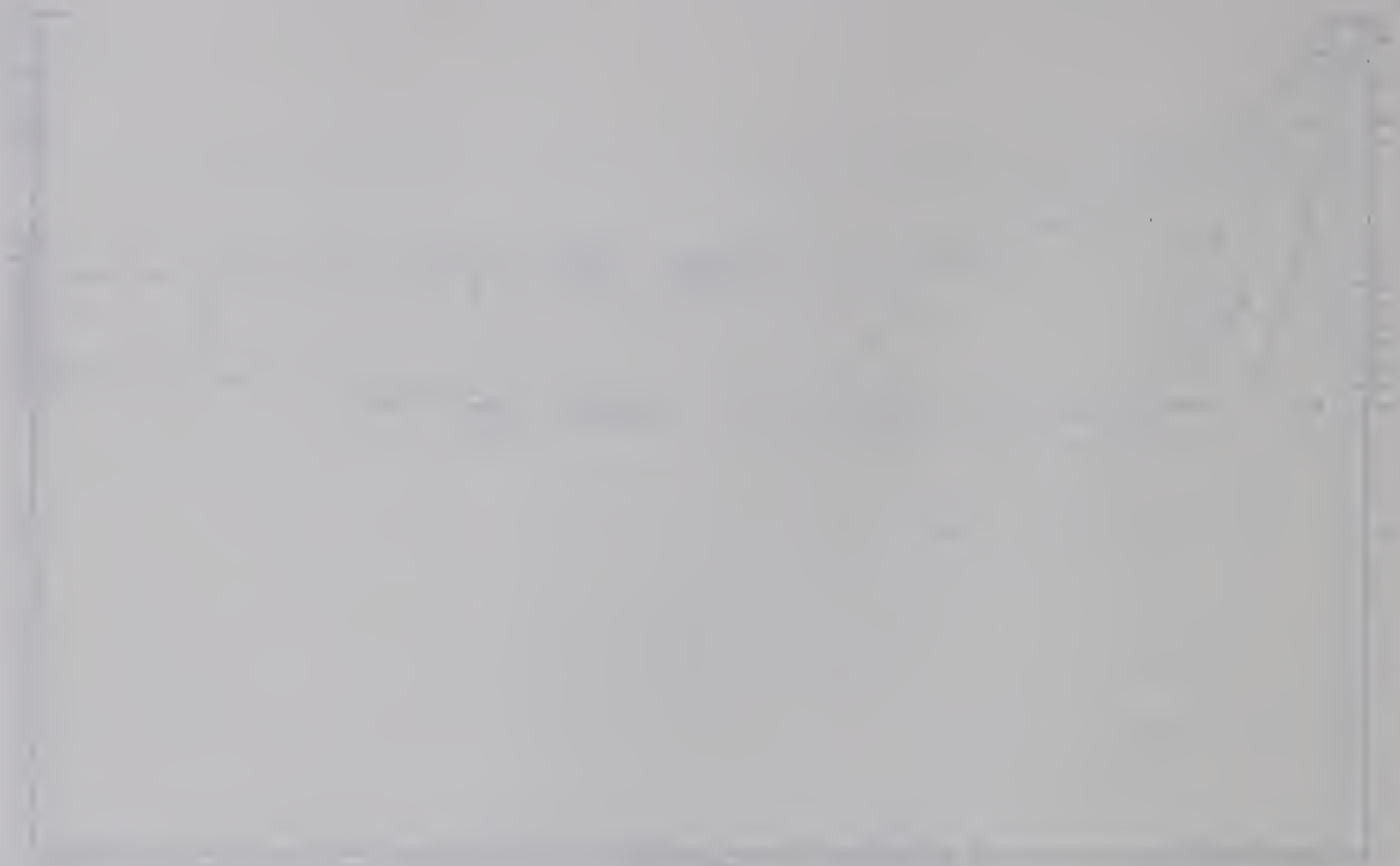
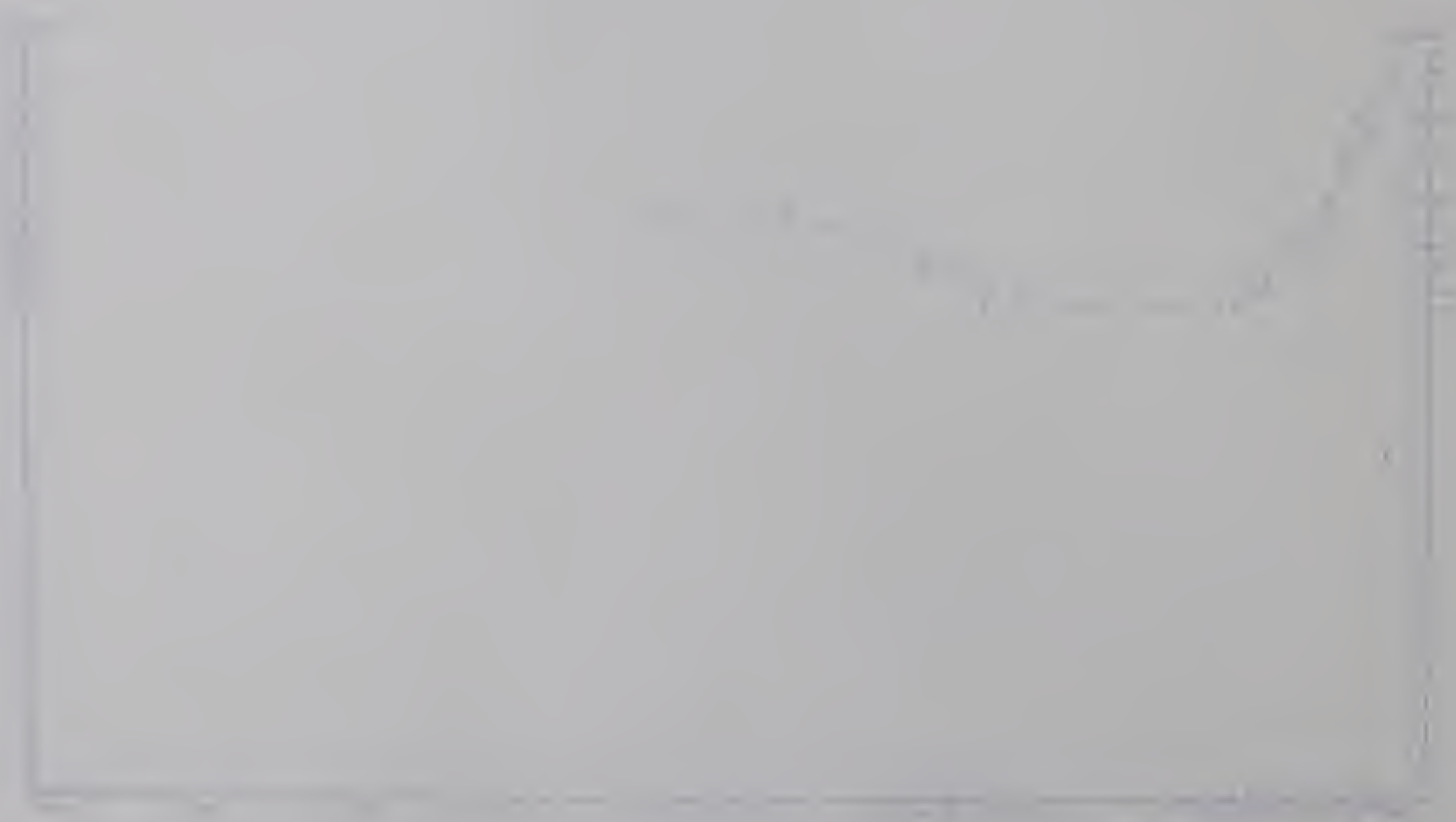


Figure 15 (b): Five Year Running Means of Central Values.





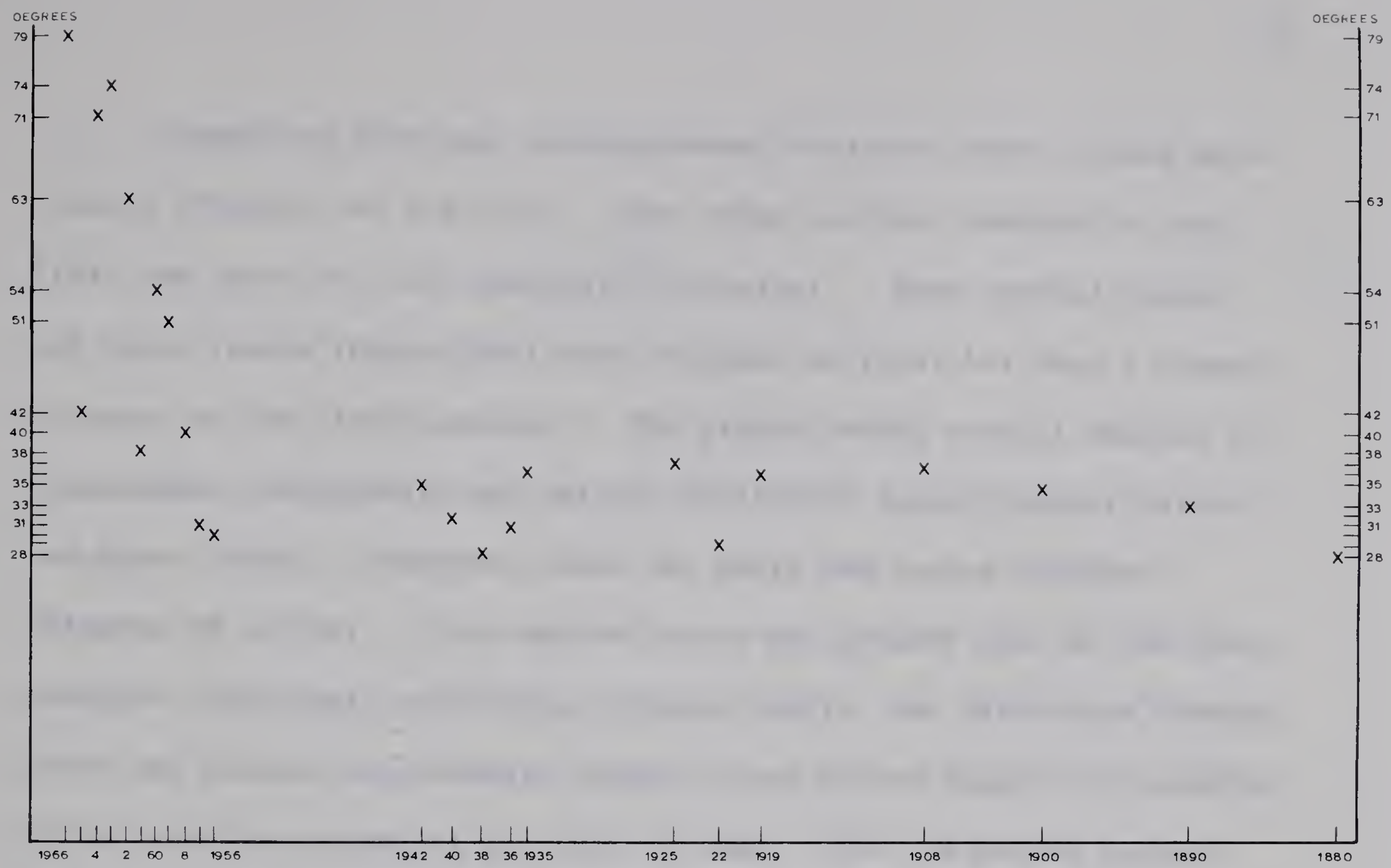


Figure 16(a): Actual Upper Limits of Slope Values on the Moraines of the Athabaska Glacier.

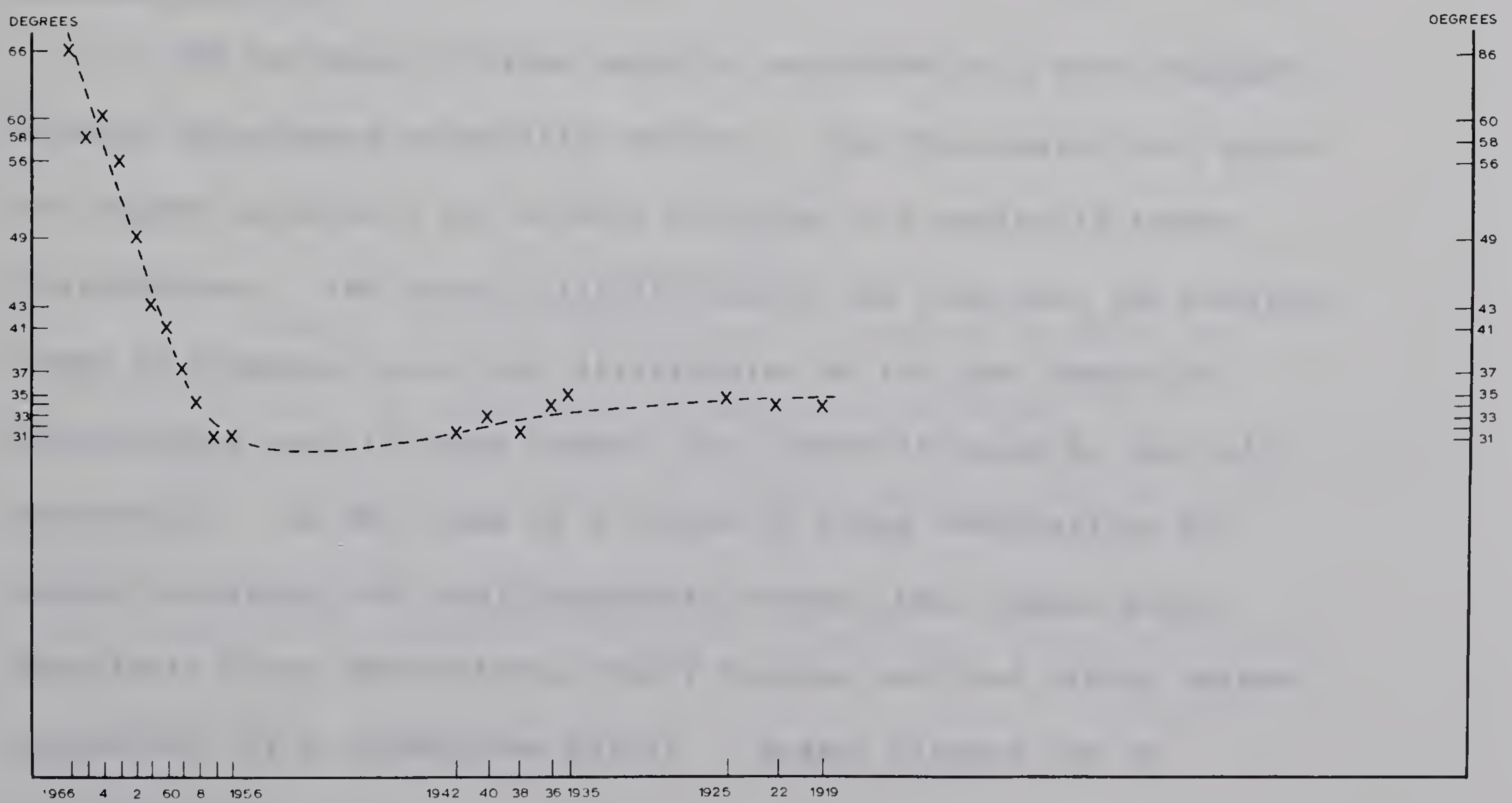
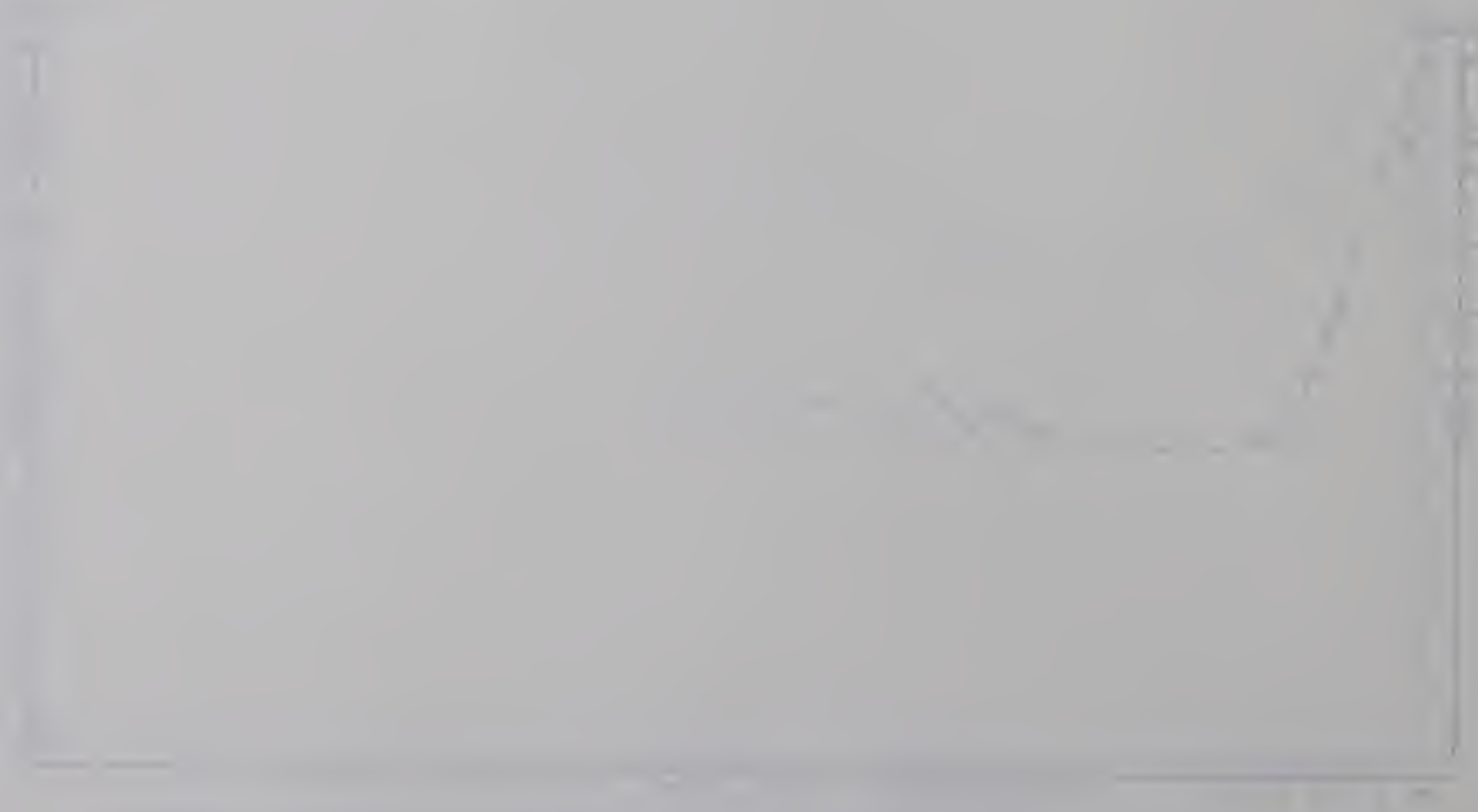


Figure 16 (b): Five Year Running Means of Upper Limits.



Graphs of five year running means illustrate these trends more clearly (Figures 14b and 15b). Mean range declines sharply for the first ten years but more gradually thereafter. Mean central values and upper limits (Figure 16b) also decrease at first but show a steady increase on the older moraines. The graphs reveal overall decline of topographic irregularity and initial decline of actual central values and upper limits. However, after ten years the latter increase (Figures 15 and 16). This may be due to the greater size of the older moraines, lithologic variations, or, more likely, the difference between Abney and Brunton measurements (Pages 33 and 34, and Figure 12), modified by the Abney measurements for 1936 to 1940. The low points (around 1950 to 1955) in the graphs of central value and upper limits (Figures 15b and 16b) may be exaggerated since the small number of slope samples on moraines between 1936 and 1958 could well give a distorted view.

Chi-Squared Test.

The decrease of slope range is expressed in a more standard form by Chi-squared probability values. The Chi-squared test gives the degree to which a set of data conforms to a perfectly random distribution. The actual distribution of the data over the possible range is compared to an even distribution of the same number of observations over the same range: the latter is known as the null hypothesis. In this case of a series of slope observations for several moraines, the null hypothesis assumes that chance would distribute slope observations evenly between zero and ninety degrees inclusively (i.e. ninety-one units). Degree classes for an

even distribution are given by the formula:-

$$DC = \frac{91}{N}$$

where DC = size of each degree class

and N = number of slope observations.

The calculation for the 1957/58 moraine is presented here as an example. This moraine has six slope observations. If these were distributed evenly there would be one observation in each successive class of fifteen and one-sixth degrees ($15^{\circ}10'$, i.e. 91/6 according to the formula above). The limits of these classes are therefore $0^{\circ}0'$, $15^{\circ}10'$, $30^{\circ}20'$, $45^{\circ}30'$, $60^{\circ}40'$, $75^{\circ}50'$ and $91^{\circ}00'$, the result of cumulative addition of the degree class value. The actual distribution of observations, according to the six classes listed above, is 0, 4, 2, 0, 0, and 0.

The actual number of observations in each of these classes is related to the expected number (unity, as defined by the null hypothesis) by the formula:-

$$Chi^2 = \frac{(0 - E)^2}{E}$$

where 0 = observed frequency of values in each class

and E = expected frequency in each class = 1.

The value of Chi^2 for the 1957/58 moraine is therefore calculated by:-

$$Chi^2 = \frac{(0 - 1)^2}{1} + \frac{(4 - 1)^2}{1} + \frac{(2 - 1)^2}{1} + \frac{(0 - 1)^2}{1} + \frac{(0 - 1)^2}{1} + \frac{(0 - 1)^2}{1}$$

$$\therefore Chi^2 = 1 + 9 + 1 + 1 + 1 + 1$$

$$\therefore \underline{\underline{Chi^2 = 14}}$$

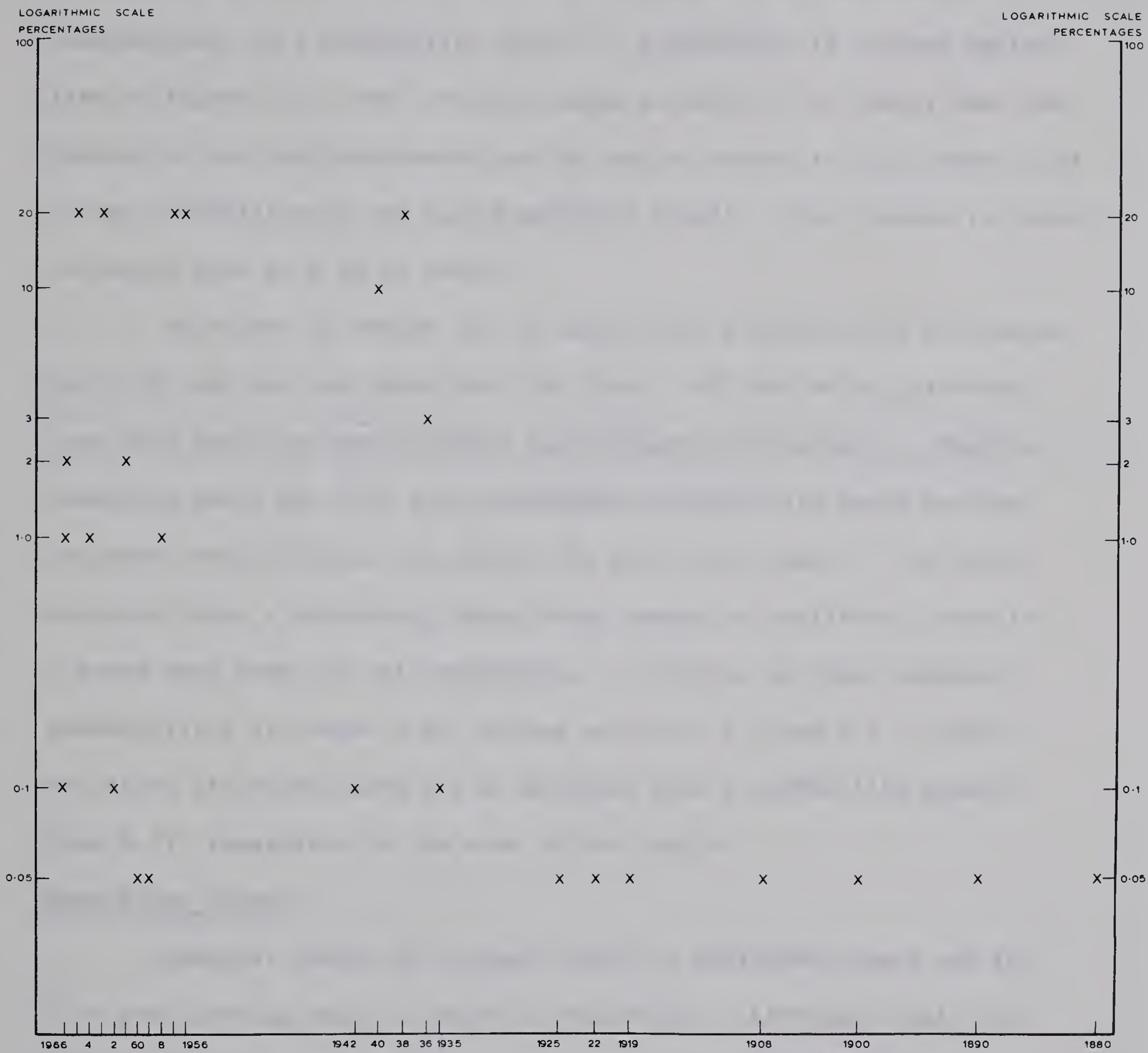


Figure 17: Chi-Squared Probability Values of Slope Distribution on the Moraines of the Athabaska Glacier.

The values for 1965/66 June, July and August have each been included, whereas on other graphs they are averaged into a single figure for 1965/66.

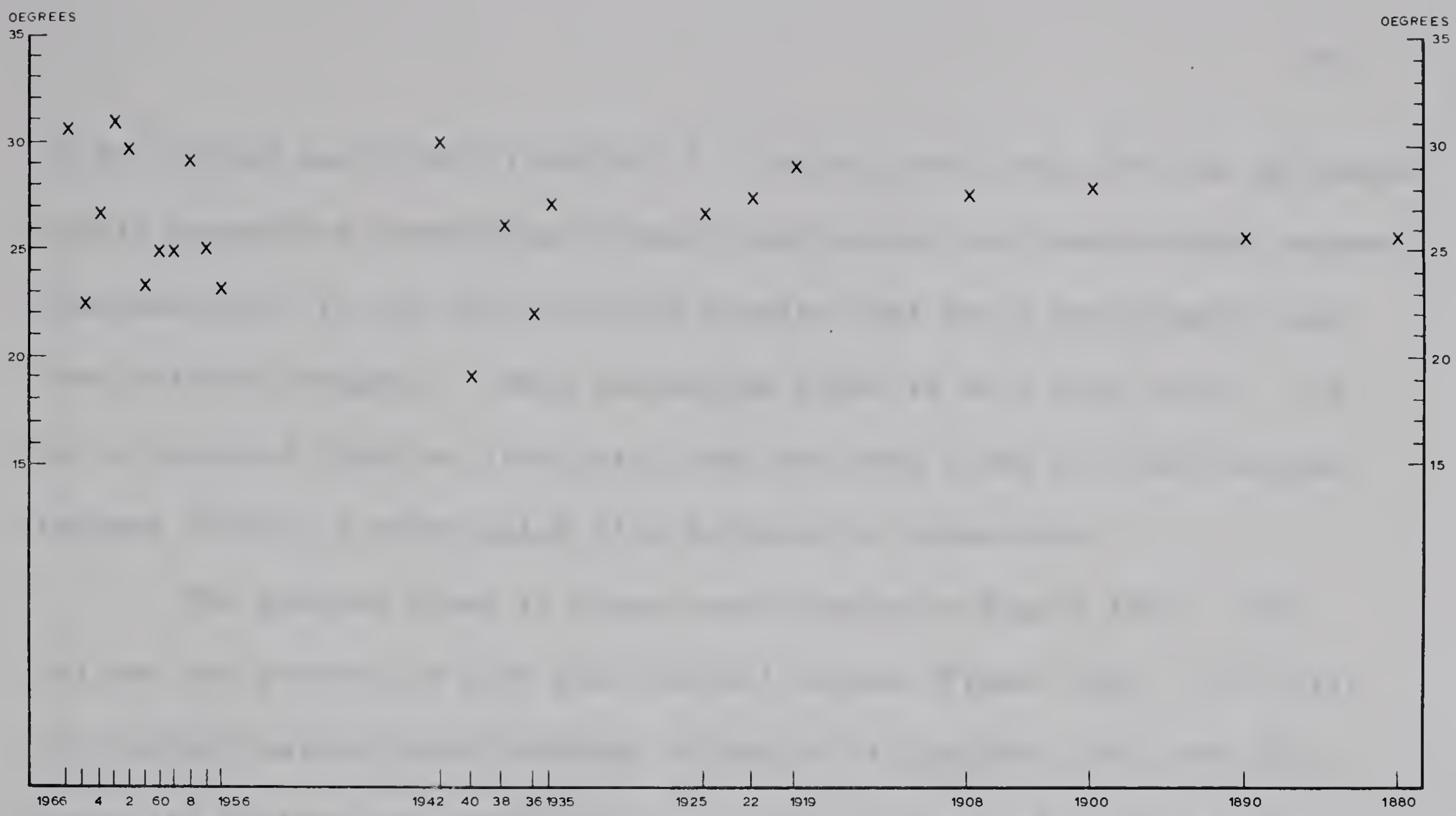


Figure 18 (a): Actual Mean Slope Values on the Moraines of the Athabaska Glacier.

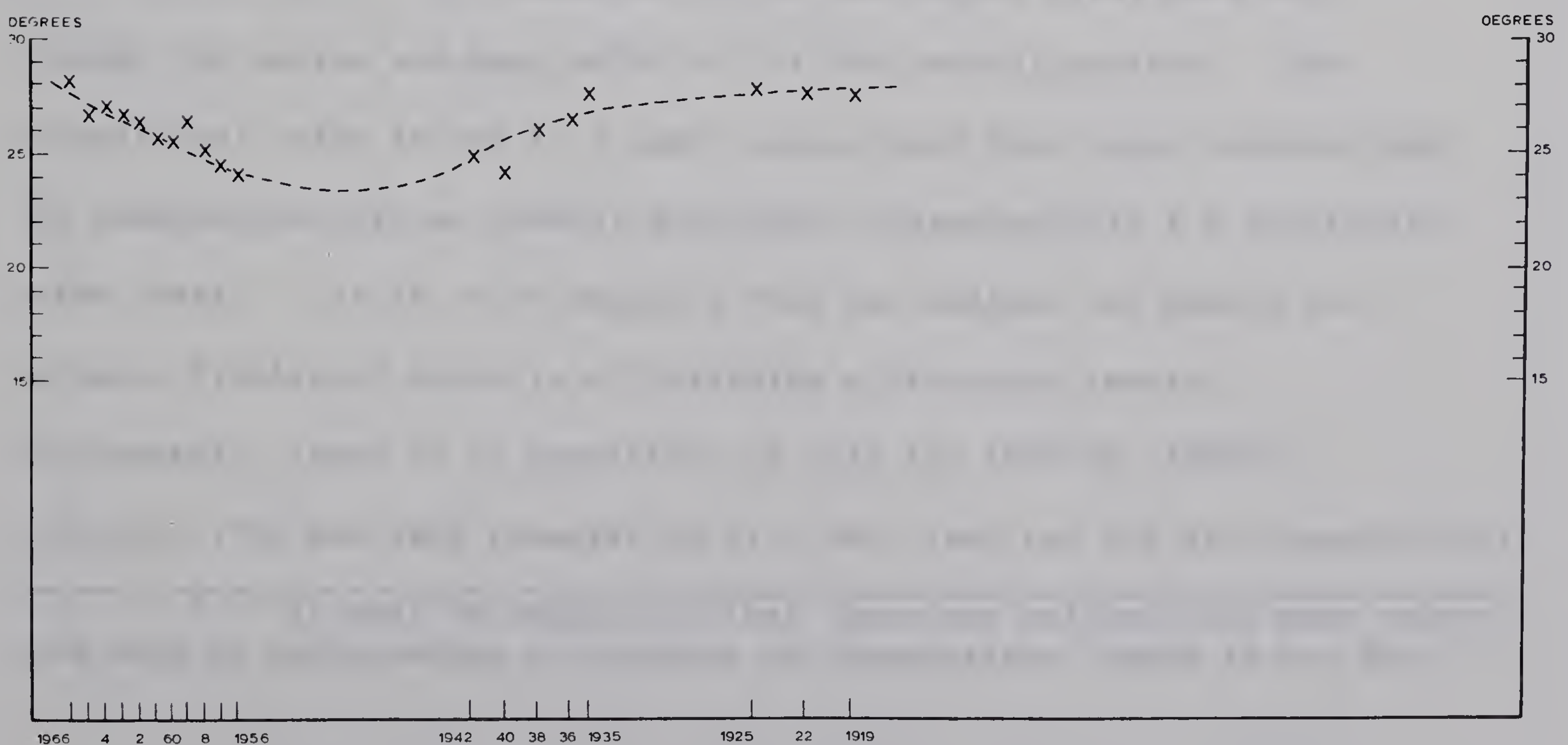
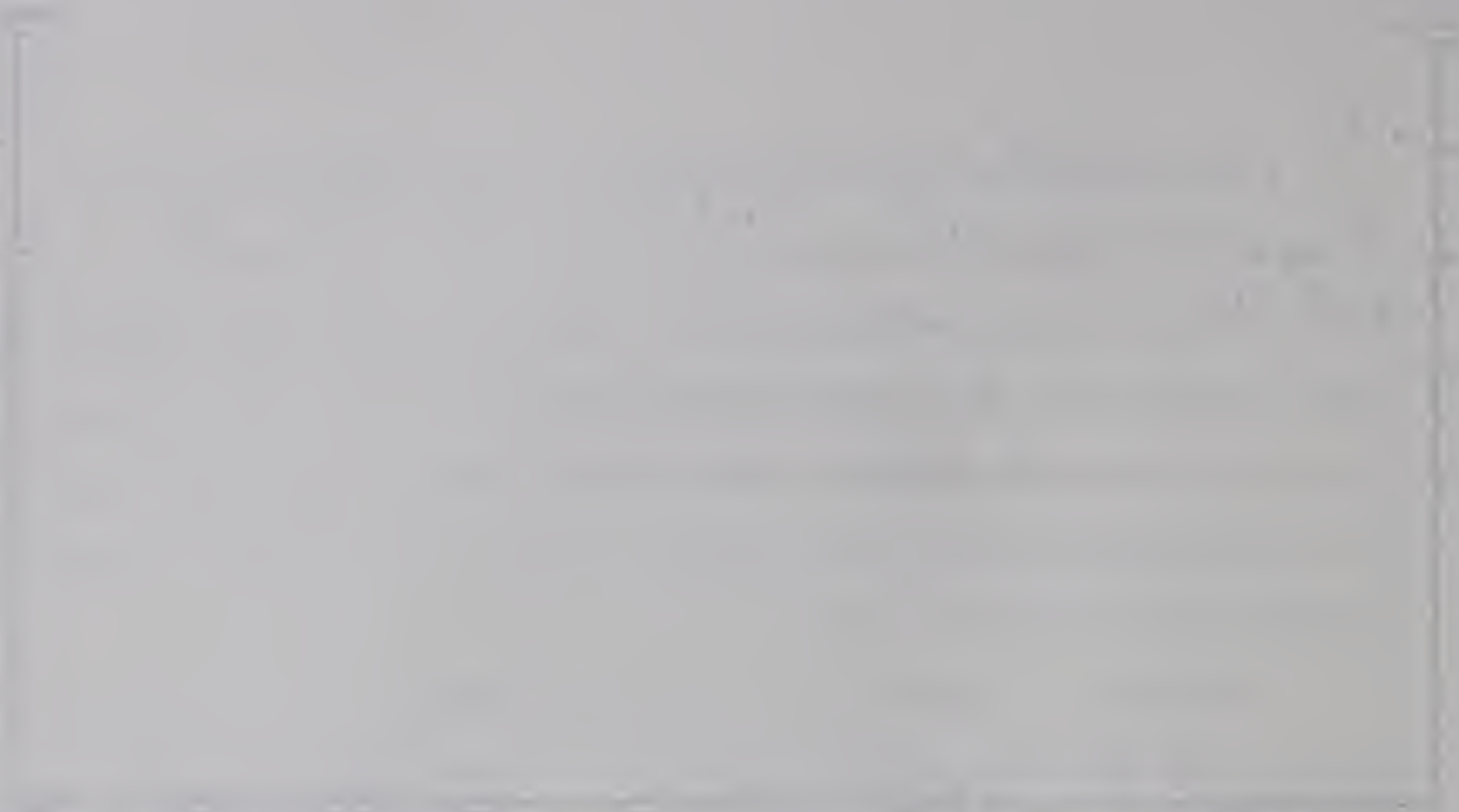
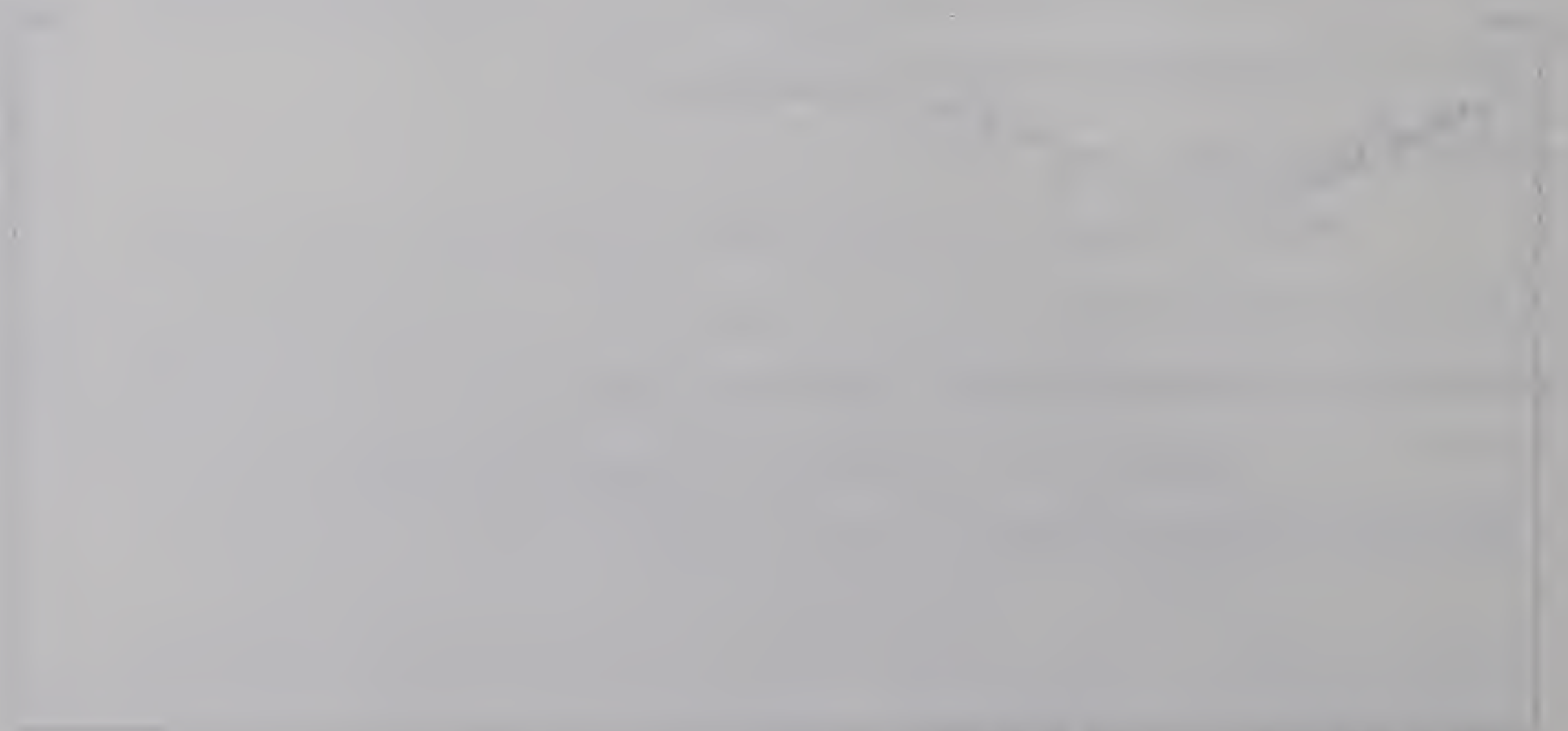


Figure 18 (b): Five Year Running Averages of Mean Slope Values.





18.83^{o} (1940) and 30.84^{o} (1962/63).[5] Points other than 1940 can be placed within asymptotes converging between twenty-seven and twenty-eight degrees. Nineteen-forty is the only pre-1958 moraine that has a measurement less than thirteen degrees. This one-degree slope is on a wide crest. If it is excepted from the 1940 data, then the mean slope for that moraine becomes 22.40^{o}, a value which fits between the asymptotes.

The general trend is shown more clearly on Figure 18b. This follows the pattern of five year central values (Figure 15b). At first the central values exceed average slopes by six degrees, but over ten years the centres and averages approach one another and become similar. Thus an initial positive skewness moves towards a normal distribution.

Medians and Modes.

Figures 19 and 20 show medians and modes and their five year running equivalents. These repeat the trends of central values and mean slopes. However, the persistence of the 1940 exception requires more explanation. The omission of the one-degree crest does not change the median and mode value to fit the overall pattern. The exceptional value is due to a small sample size (six slope observations) in combination with an unusual geomorphic characteristic (a relatively wide crest). It is to be expected that the smaller the sample the greater likelihood there is of obtaining a distorted result. Fortunately, there is no repetition of this for 1957/58, 1956/57, 1955/56, 1938 and 1922 (samples of six, two, two, two and six respectively).

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5 It must be emphasized that these are arithmetical mean values and bear no relationship to accuracy of observations (Pages 19 and 20).

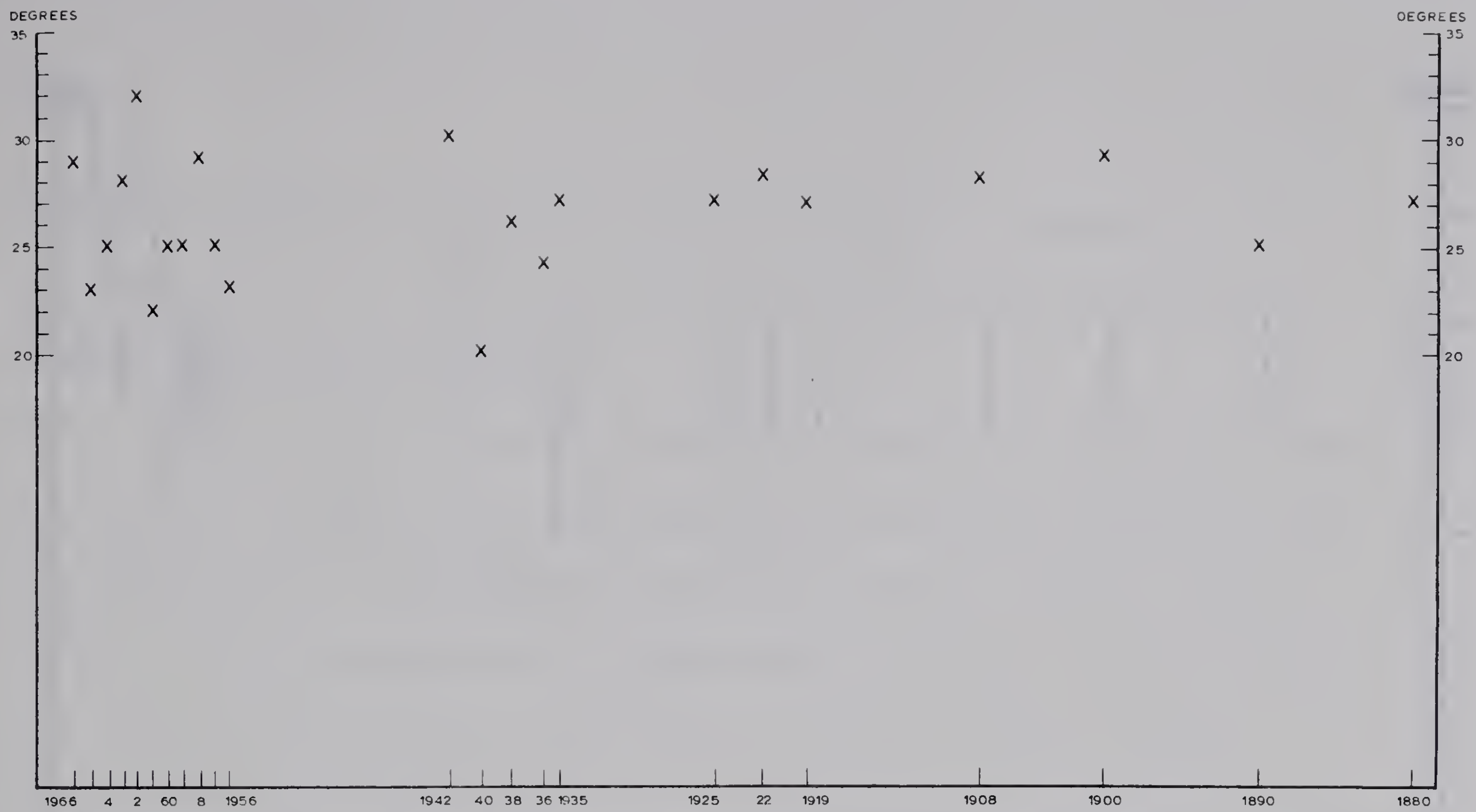


Figure 19(a): Actual Medians of Slope Values on the Moraines of the Athabaska Glacier.

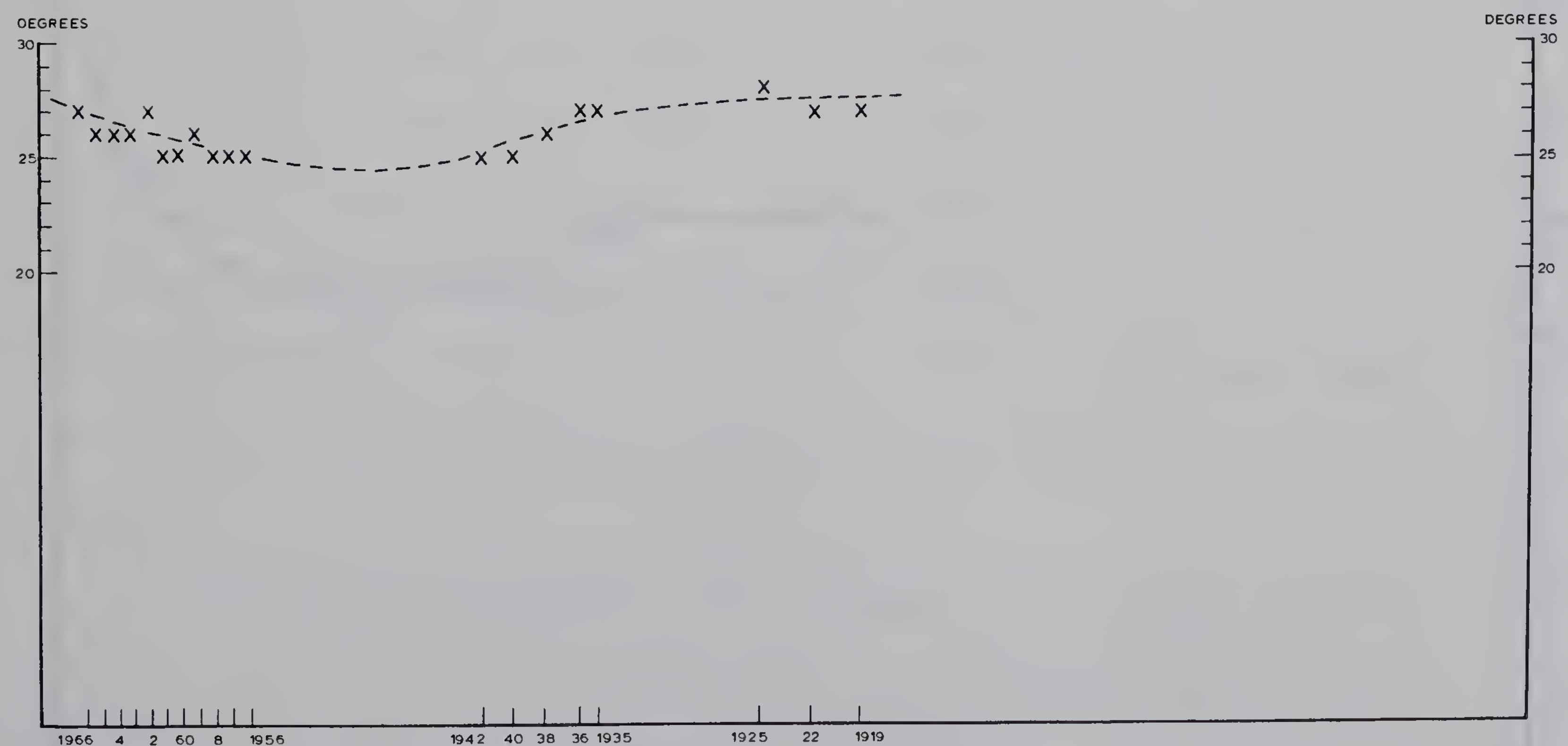
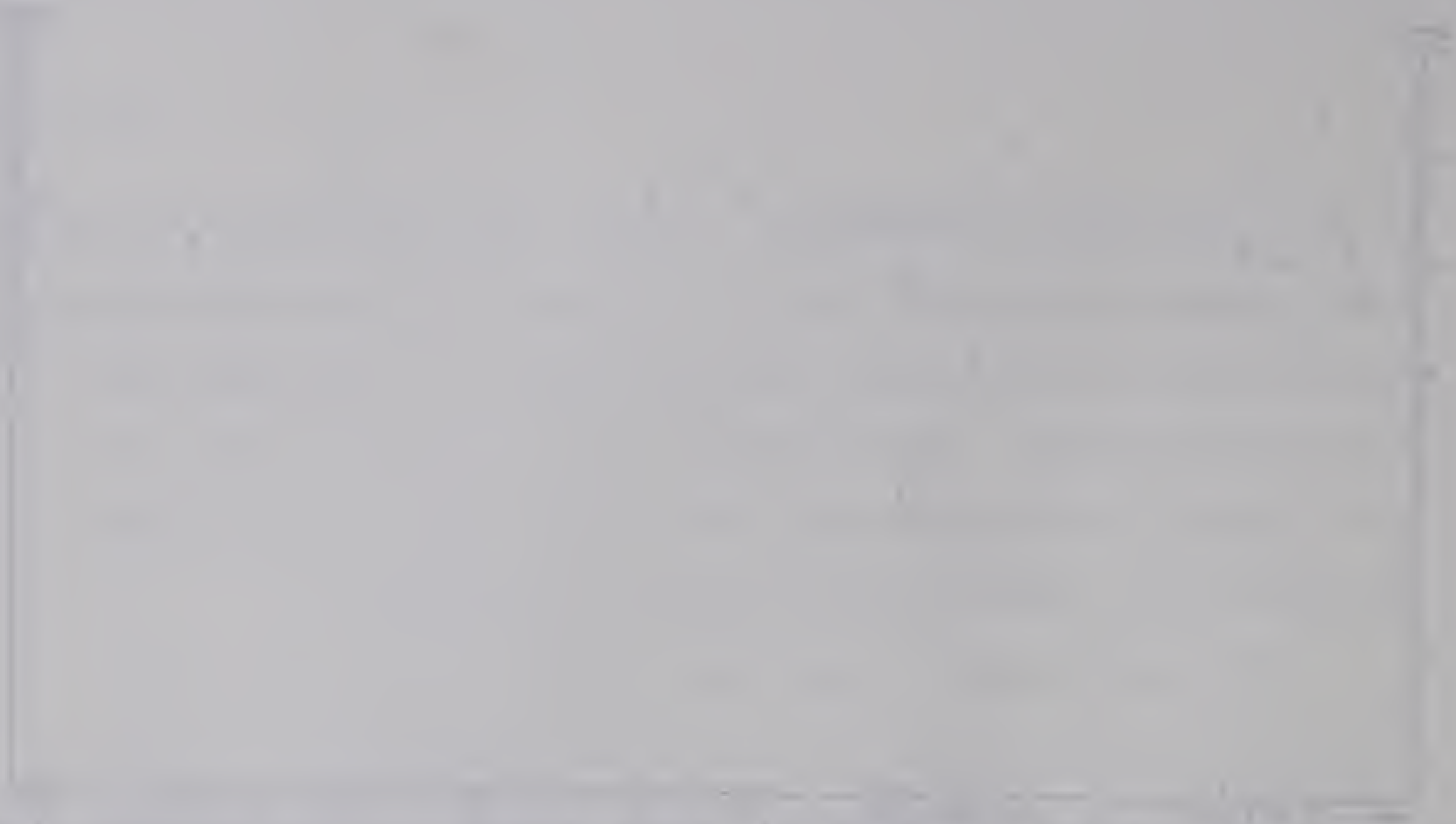
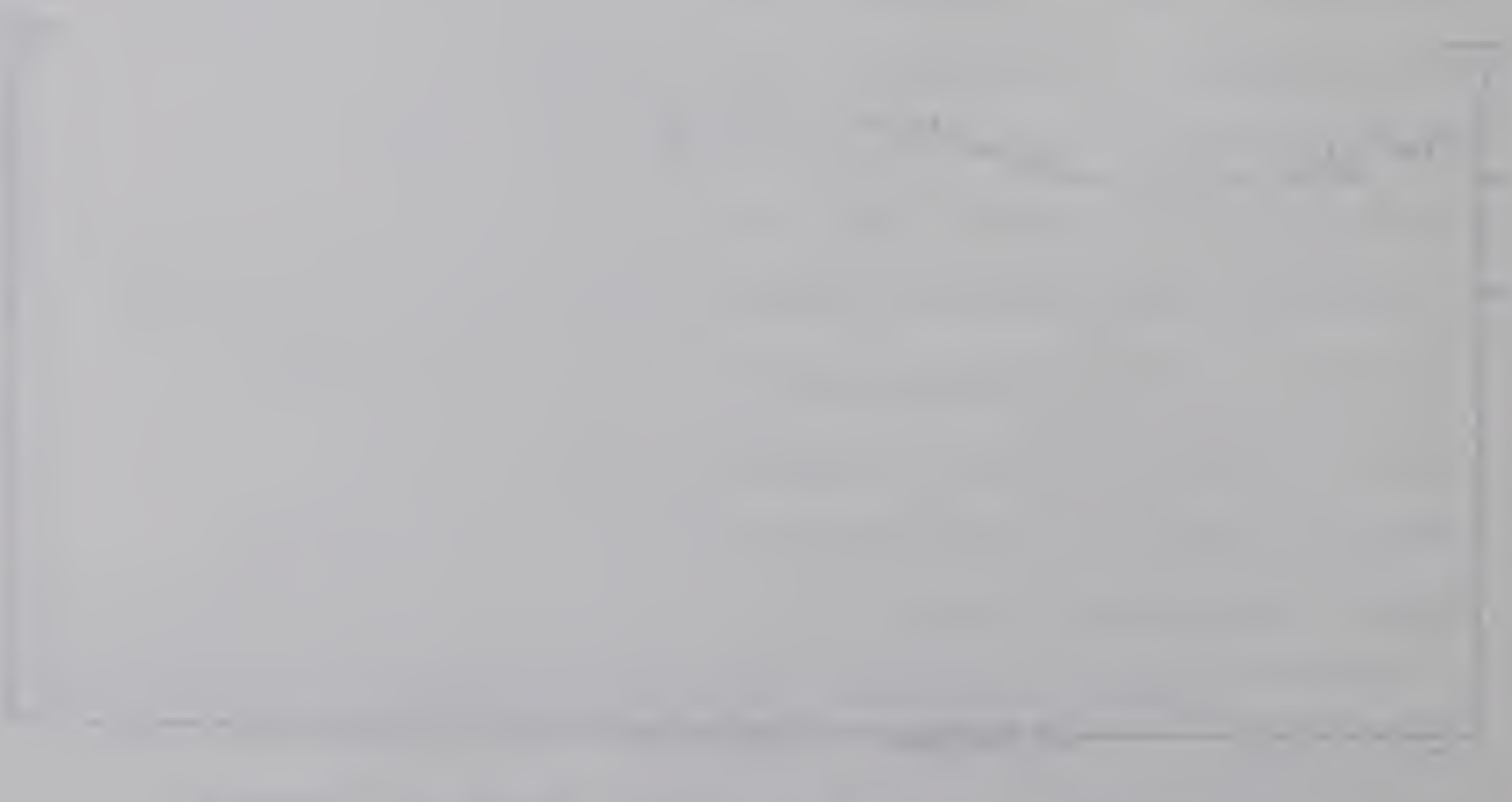


Figure 19 (b): Five Year Running Means of Medians.





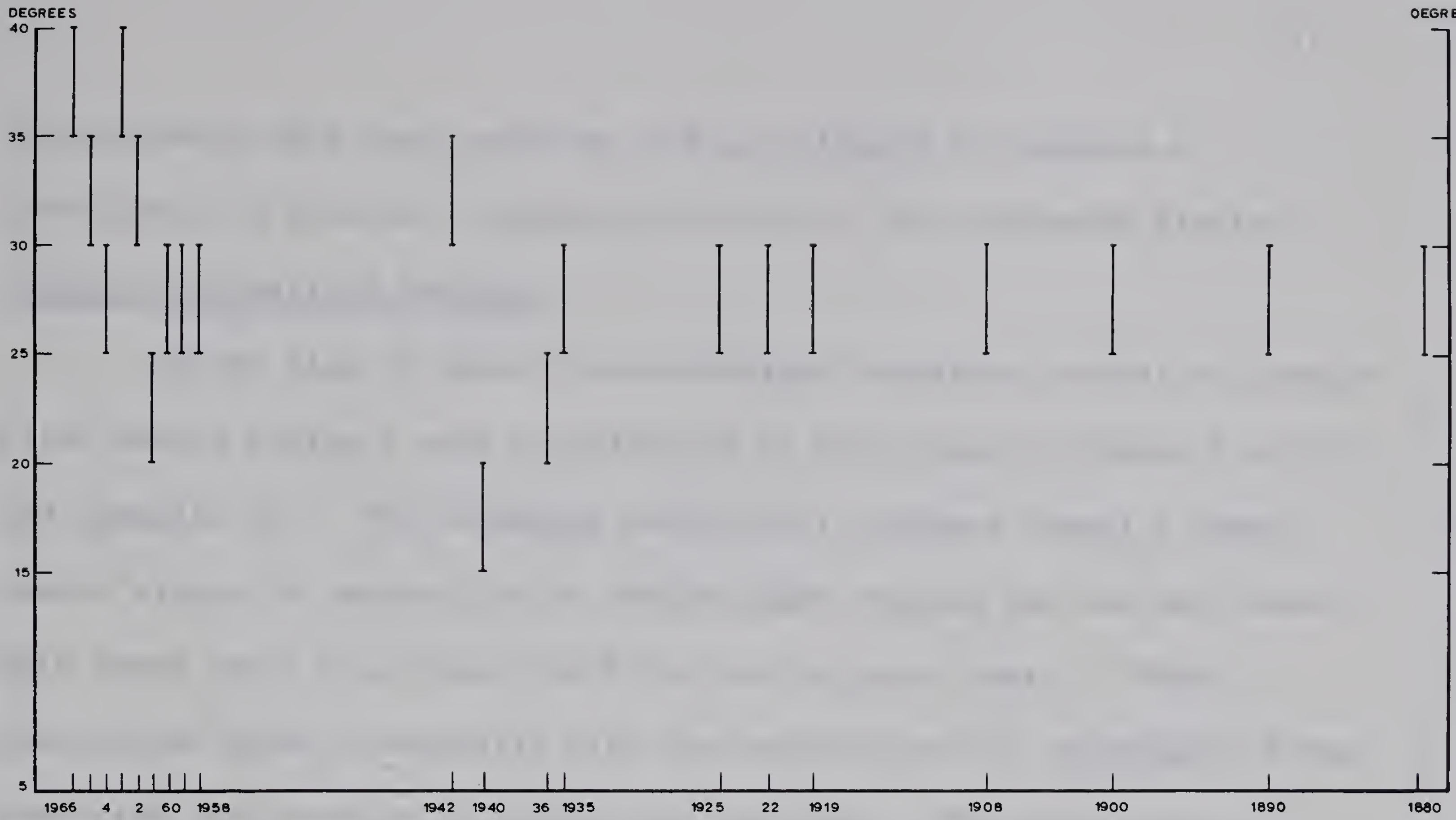


Figure 20(a): Actual Modes of Slope Values on the Moraines of the Athabaska Glacier.

Modes for 1956/57, 1955/56 and 1938 have not been included. These moraines have only two slope recordings.

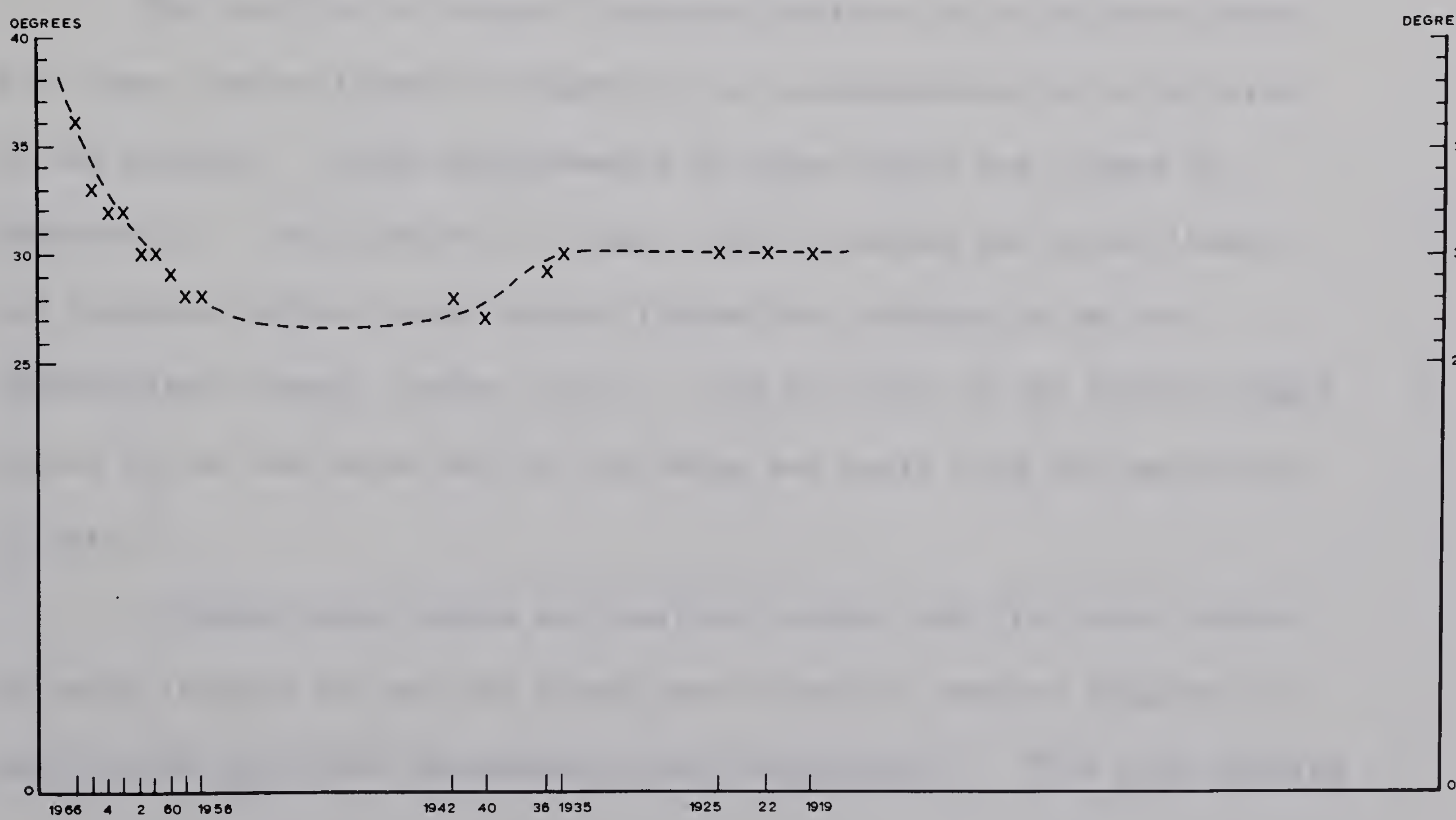


Figure 20 (b): Five Year Running Means of Modes.

Alternatively this fact could be used as evidence to indicate a consistency of morainal topography in front of the Athabaska Glacier.

Summary of Numerical Analyses.

At the time of deposition recessional moraines consist of loosely piled debris having a wide distribution of slope angles (Plates 5 to 10 and Appendix B). The foregoing statistical analyses reveal a trend toward slopes of twenty-five to twenty-eight degrees for the main faces. This trend takes place over the first six or seven years. These conclusions agree essentially with the descriptions of topographic forms preceding this section on statistical analyses. The statistical methods lack discussion of slope form but do offer an objective view of the rates of change of various parameters of the slopes, such as mean and median values. The numerical presentation of these parameters permits a graphical representation of sequential changes.

The profiles of several moraines include large boulders whose size (over twelve inches in diameter) is incommensurate with the size of the moraine. Slope measurements on these rocks are ringed in Appendix B. Calculations of range, centre, median and upper limits are repeated without these facets (hereafter referred to as the "generalized" range, centre, etc.). All but four of the eleven ringed values lie at the upper end of the range and apart from the main body of data.

Although some values are smaller, single and five year trends of range (Figure 21) and the single year trend of centres (Figure 22) vary little from their non-generalized counterparts. Five year centres

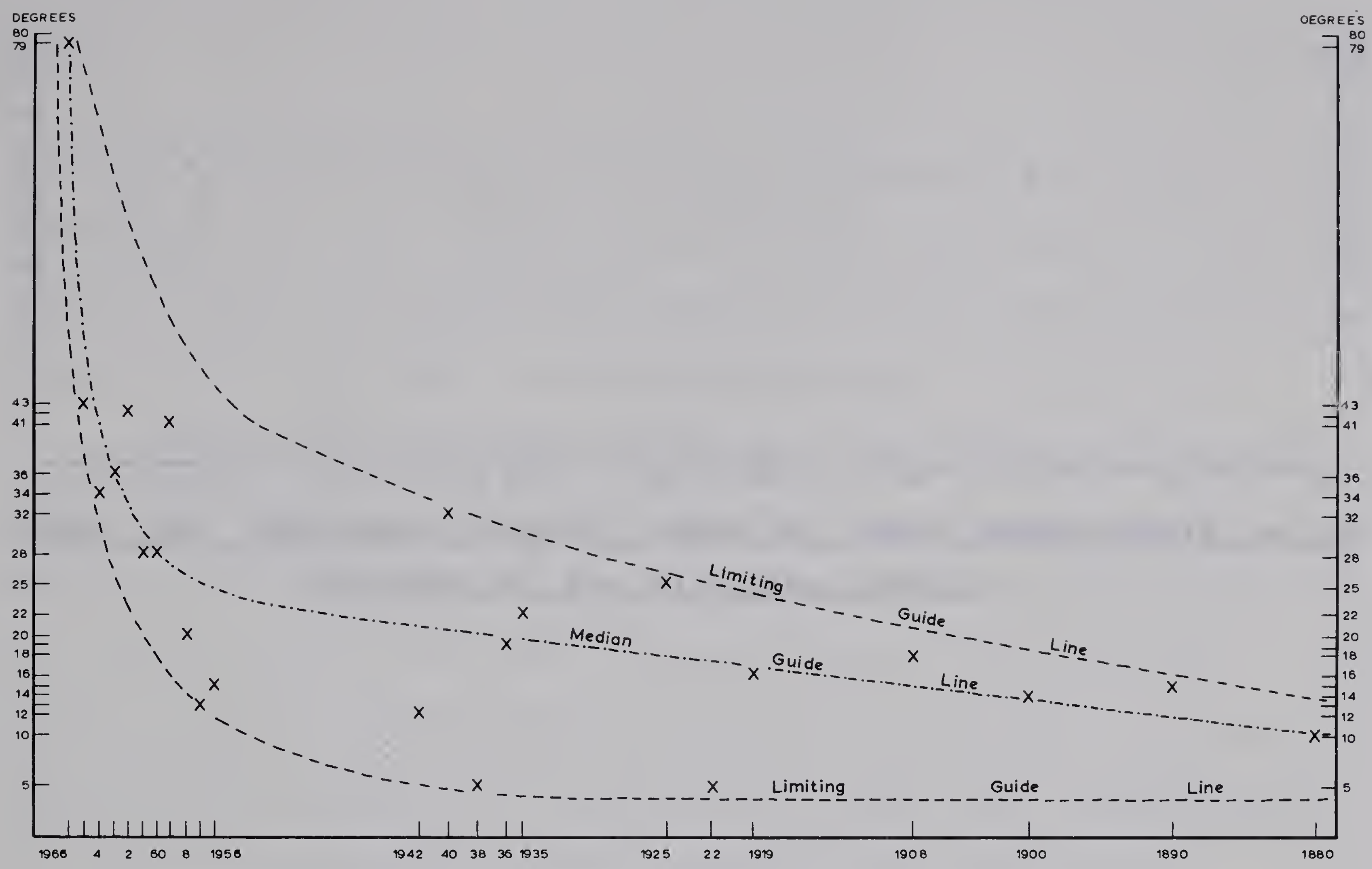


Figure 21(a): Generalized Ranges of Slope Values on the Moraines of the Athabaska Glacier.

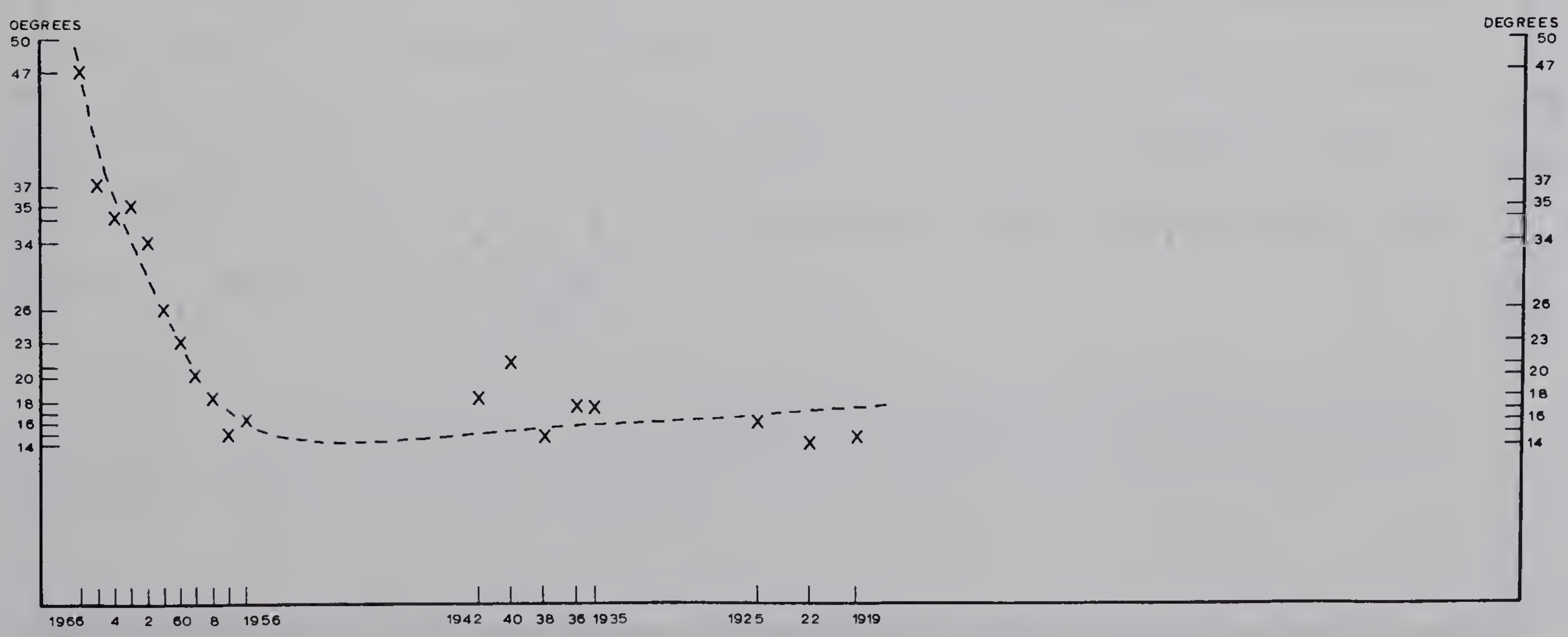


Figure 21 (b): Five Year Running Means of Generalized Ranges.

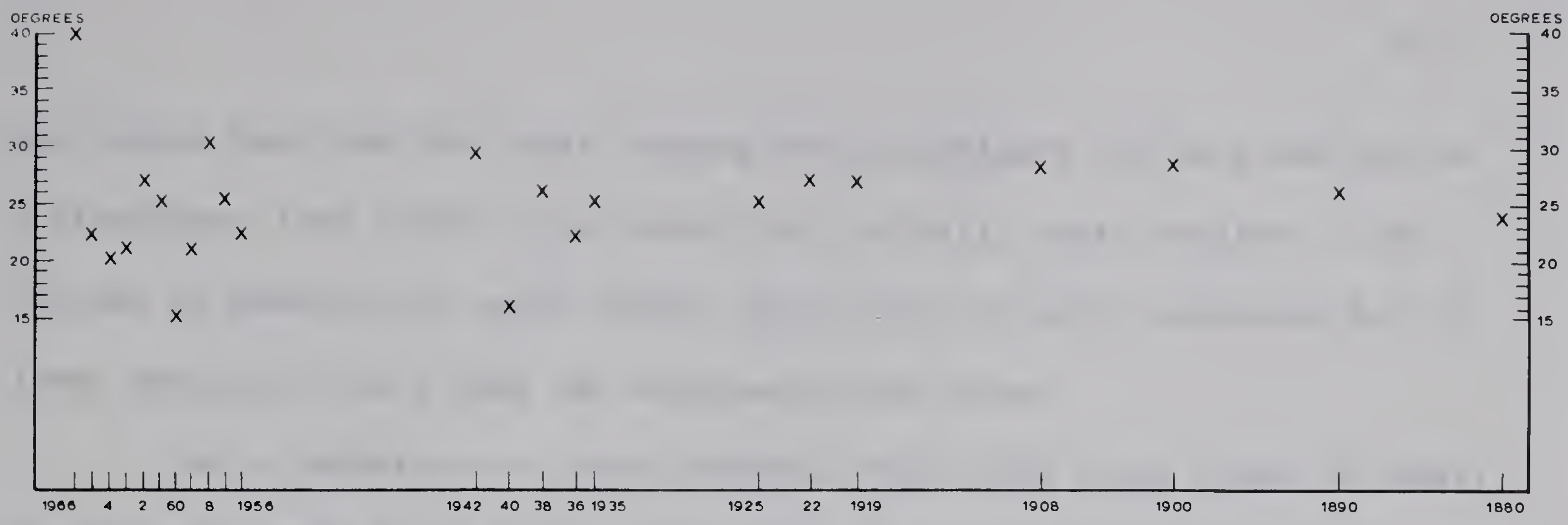


Figure 22: Generalized Central Values of Slope Measurements on the Moraines of the Athabaska Glacier.

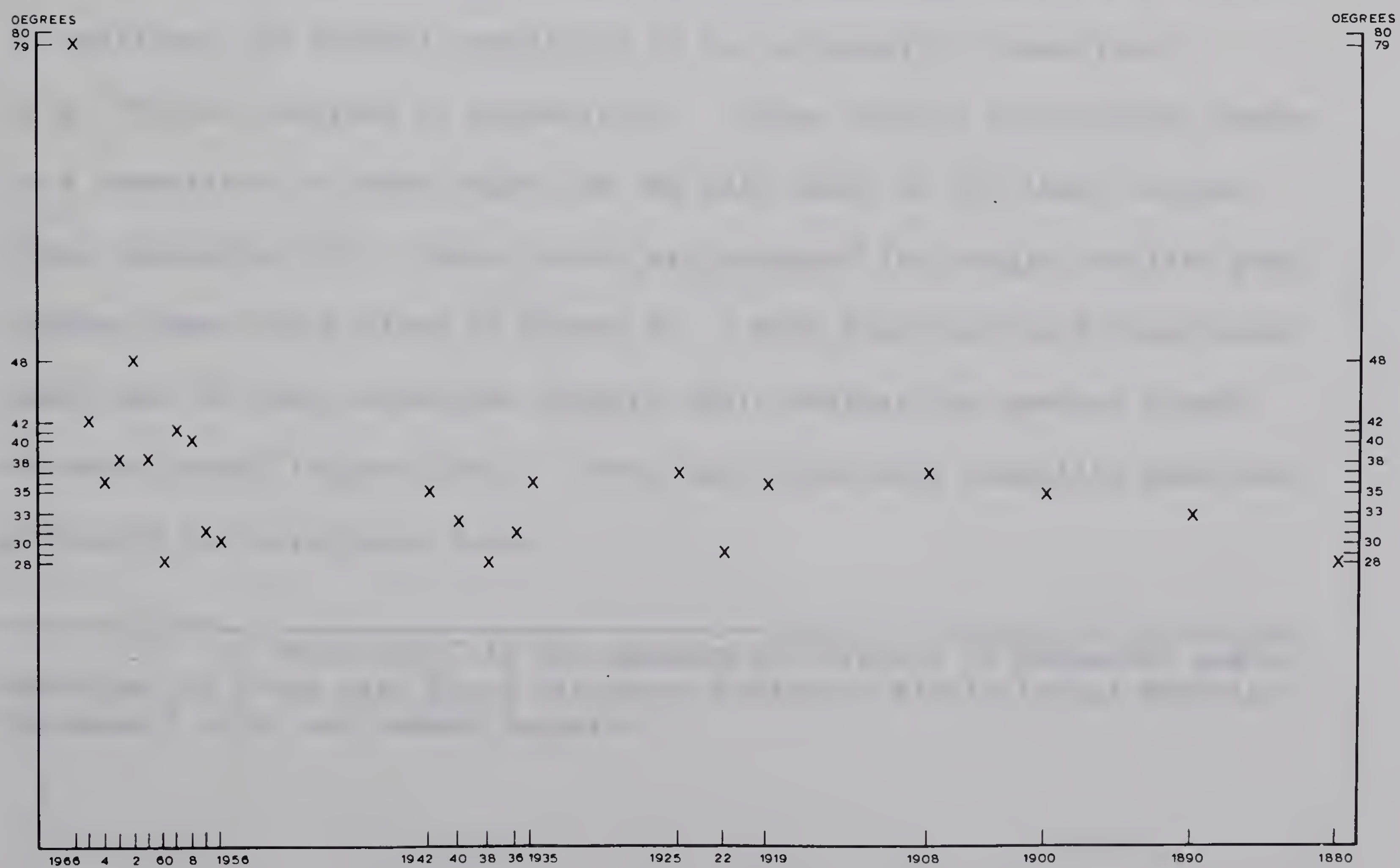


Figure 23: Generalized Upper Limits of Slope Measurements on the Moraines of the Athabaska Glacier.

and single year and five year running medians (Figure 23) vary and lie on a straighter line rather than exhibiting initially rapid decline. The decline of generalized upper limits (Figure 24) is more consistent but of lower absolute values than the non-generalized data.

The elimination of these boulders shows that steep slopes on small debris exist only for a year; after that the general maximum is forty degrees and beyond ten years is thirty-five degrees. Changes are seen to be rapid over the first year; thereafter changes occur relatively slowly. This is consistent with the discussion on geomorphic processes - most examples are found on the 1965/66 moraine (Table III). Subsequently the slow process of surface rainwash is the most important activity.

Slope Variations According to Aspect.

Precipitation, evaporation and exposure vary according to aspect. In addition, the initial deposition is not necessarily symmetrical (e.g. 1965/66, section G, Appendix A). These effects are briefly checked by a comparison of slope angles on the main faces of the Abney section lines (Appendix C)[6]. These values are averaged for single and five year running means and plotted on Figure 25. Both front and back faces show great year to year variations (Figure 25a), whereas the general trends are more steady (Figure 25b). Front faces show more stability than the gradually declining back faces.

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6 A "main face" is the maximum (or overall if measured) angle. Selection of these main faces discounts boulders, glaciofluvial material, "en-masse" slips and summer deposits.

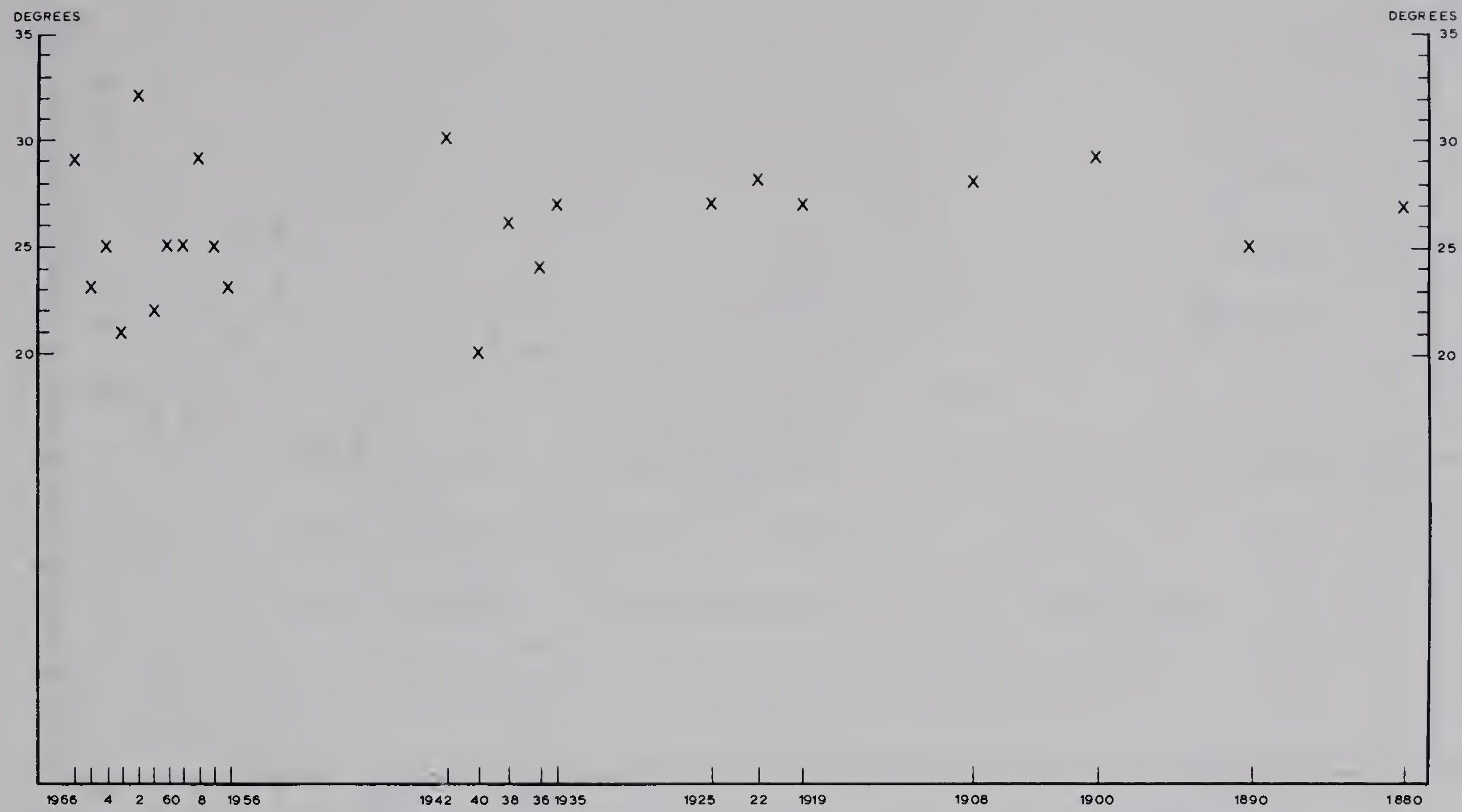


Figure 24(a): Generalized Medians of Slope Measurements on the Moraines of the Athabaska Glacier.

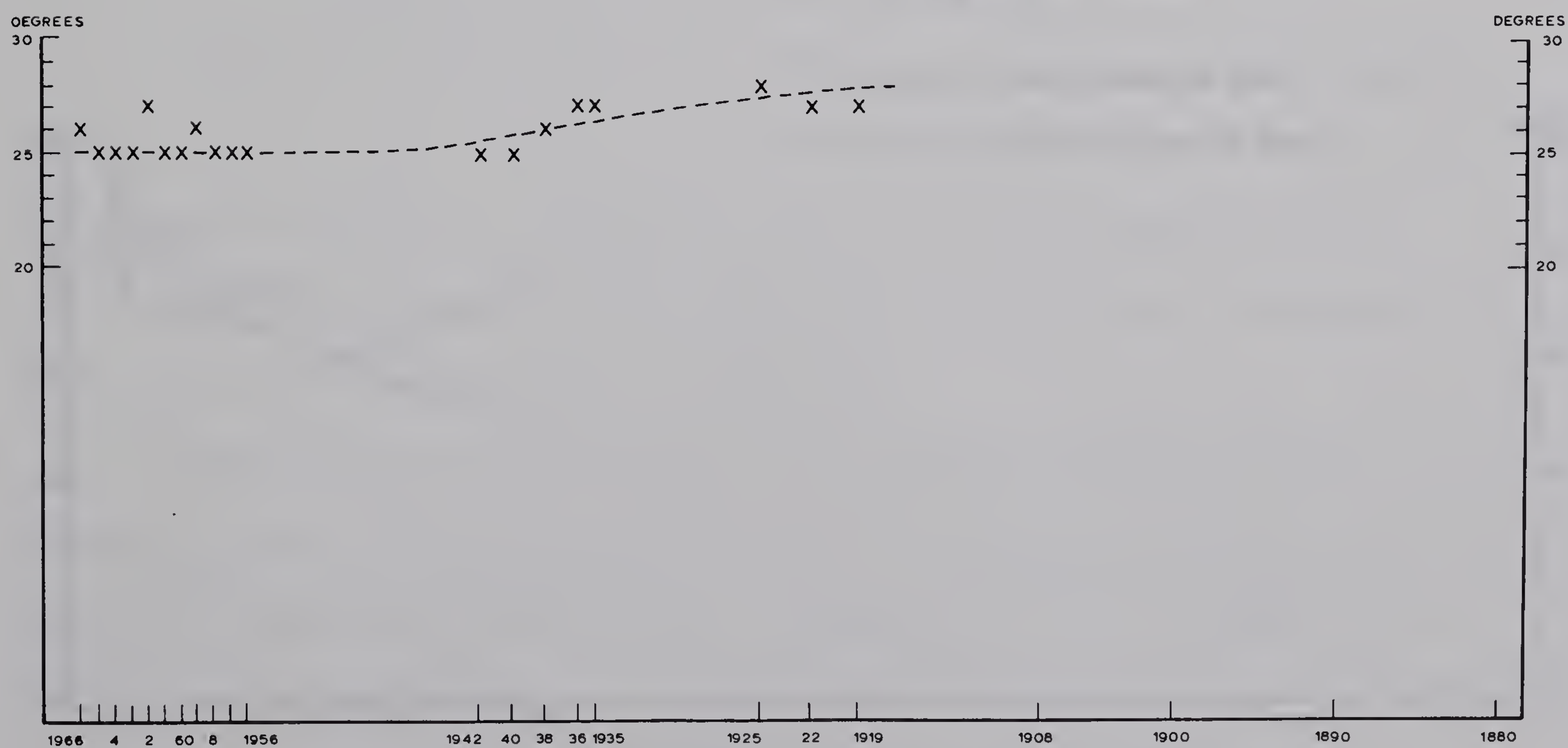
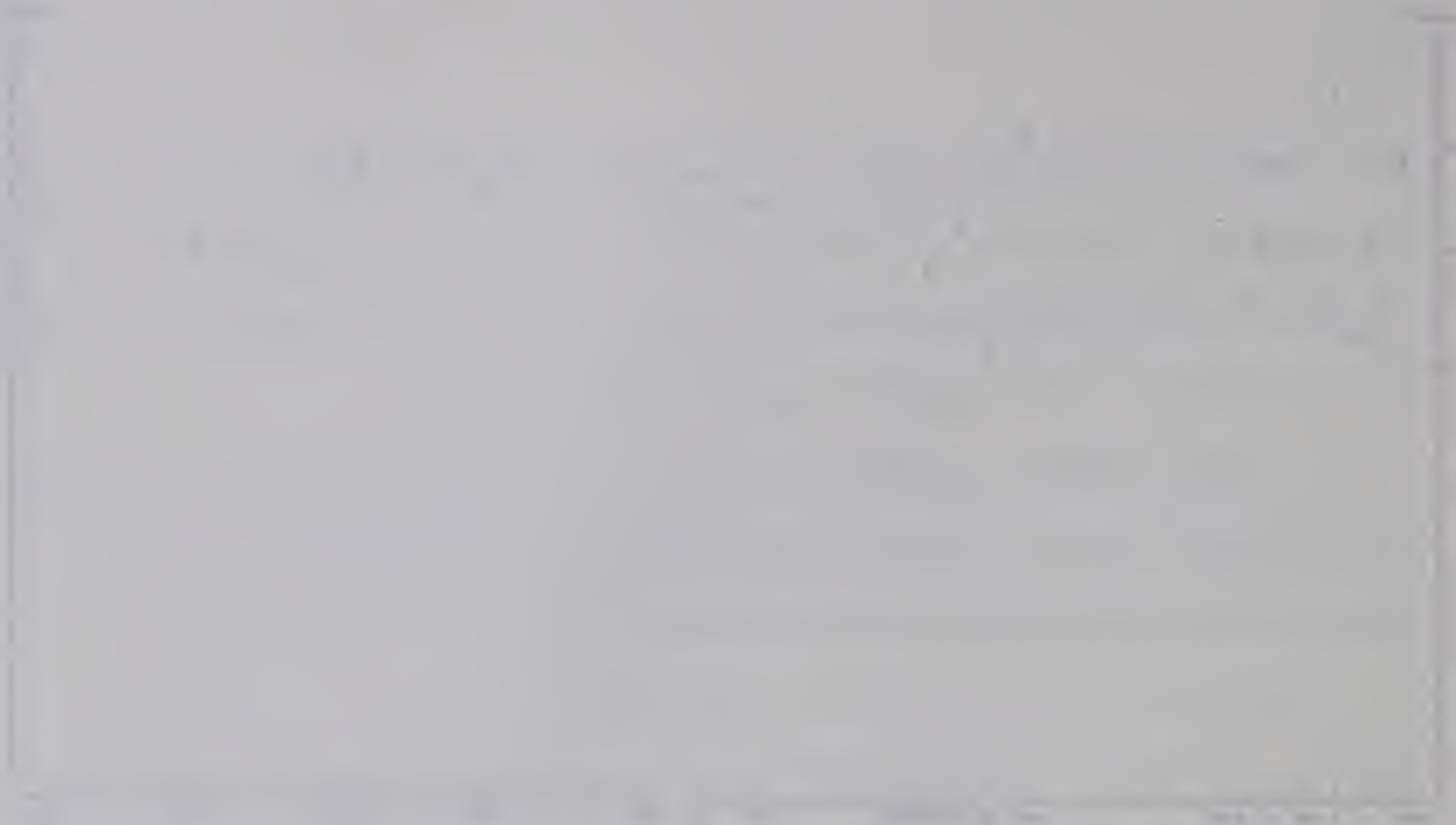


Figure 24 (b): Five Year Running Means of Generalized Medians.



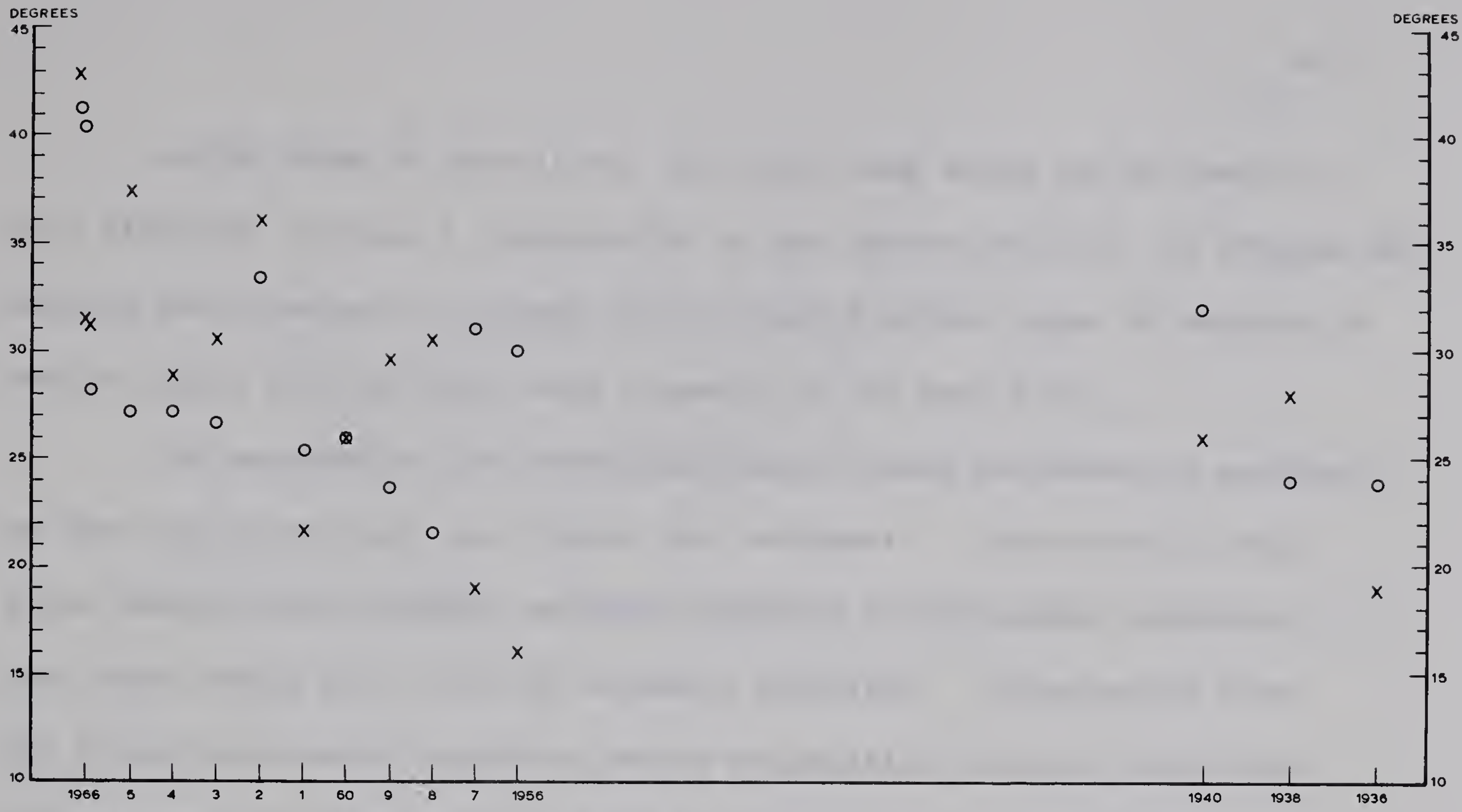


Figure 25(a): Variations of Slope Measurements on the Moraines of the Athabaska Glacier according to Aspect.

Slope variations according to aspect are calculated on the basis of Abney Level Sections only

The values for 1965/66 June, July and August have each been included, whereas on other graphs they are averaged into a single figure for 1965/66.

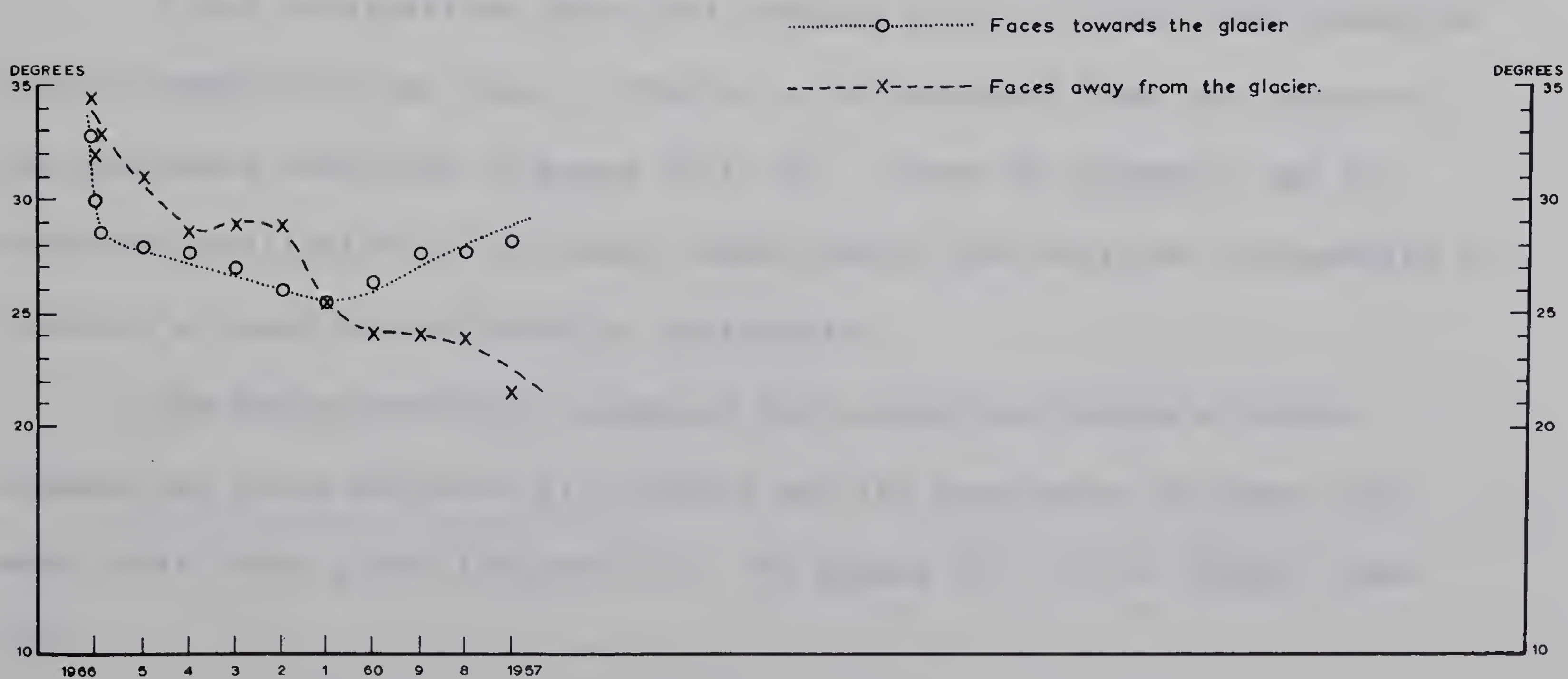


Figure 25(b): Five Year Running Means of Aspect Variations.

At the time of deposition, the front face angle can be small or zero (1965/66, section H, Appendix A) as the debris rests on ice (Figure 26). Melting and subsequent collapse or settling of debris seems to maintain a smaller angle for the front face compared to the back face.

The moraines at the Athabaska Glacier trend northwest to southeast, so that the front faces are toward the southwest. Consequently these faces receive more sunshine and more exposure to the almost continual cold wind coming down from the Columbia Icefields. Evaporation from the front faces would therefore exceed evaporation from the back faces. Furthermore, the wind tends to keep the front faces clear of snow. Thus, more moisture is available to the back slopes and therefore more surface wash. This could account for the decline of the back faces relative to the front faces (Figure 25).

Irregularities on the Moraine Surfaces

Field observations show that surface details become less irregular (less "rough") through time. This is to be expected from the nature of the processes described on pages 20 to 22. Loss of roughness can be expressed qualitatively by visual comparison of the sections in Appendix A; however, a quantitative index is preferable.

The method used here compares the cumulative change of slope between any three adjacent plot points and the cumulative distance over which this takes place (Figure 27). On Figure 27, 27c is rougher than 27d.

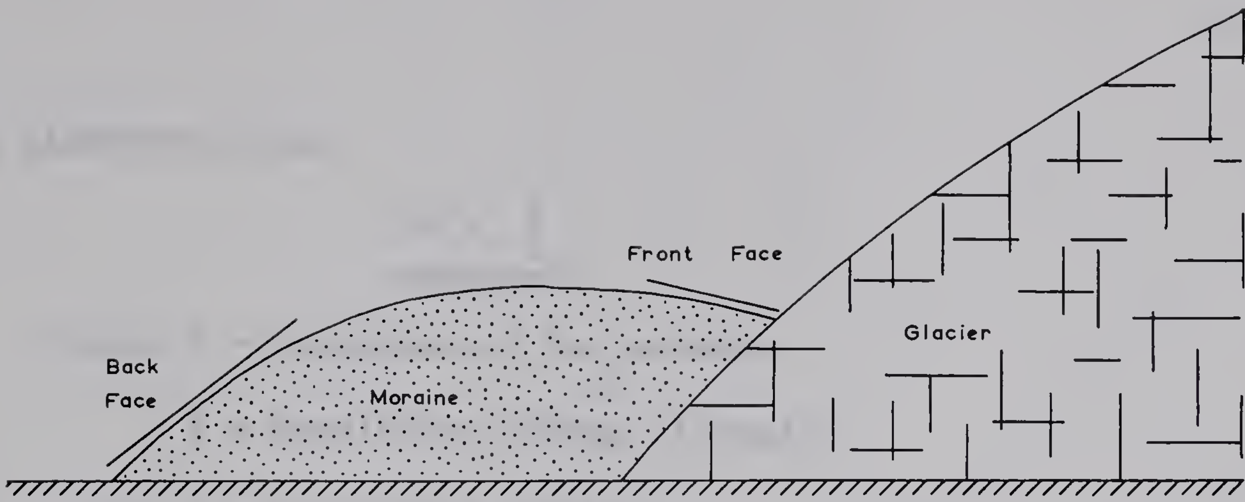


Figure 26: Explanation of 1965/66 Section H - Front Face resting on Ice.

Figure 27(a): Surfaces as drawn in Appendix I.

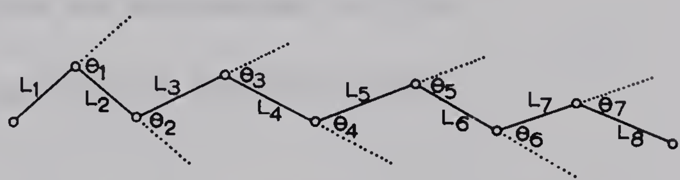


Figure 27(b): Measurement of Roughness.

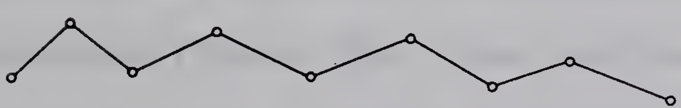


Figure 27(c): Compare with Figure 27(d).

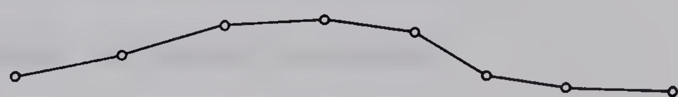
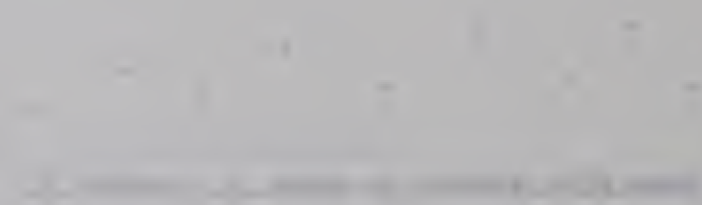


Figure 27(d): Less Surface Roughness than in Figure 27(c).

Figure 27: Calculation of Surface Roughness.



In algebraic form,

$$R = \frac{\theta}{L}$$

where R = roughness of the moraine,

θ = cumulative change of angle

and L = cumulative length.

Referring to Figure 27b,

$$R = \frac{\theta_1 + \theta_2 + \theta_3 + \theta_4 + \theta_5 + \ldots\ldots. + \theta_n}{l_1 + l_2 + l_3 + l_4 + l_5 + \ldots\ldots. + l_n}$$

Values of θ were measured with the aid of a guide, redrawn here as Figure 28, on transparent plastic. The base line was laid over each individual length l, so that the centre of the radiating guide lines lay over the point at which θ was to be measured. The next plot point to the right was measured for the angle θ to the nearest ten degrees, given by the angle of the nearest radiating guide line as subtended on the base line. This operation was repeated for each plot point on the sections of Appendix A.

The cumulative length L was measured by use of a map-distance measuring wheel. The results are tabulated in Appendix D and plotted on Figure 29.

Progressive smoothing is obvious from Figure 29, far more so than for any expression of slope decline. Five year running means of roughness (Figure 29b) show only one rise between adjacent readings (33.59 to 33.64, 1957/58 to 1956/57 respectively). The trend of Figure 29a (actual roughness values) is broken by the years 1936 to 1940: it is these anomalies which cause the rise in five year running

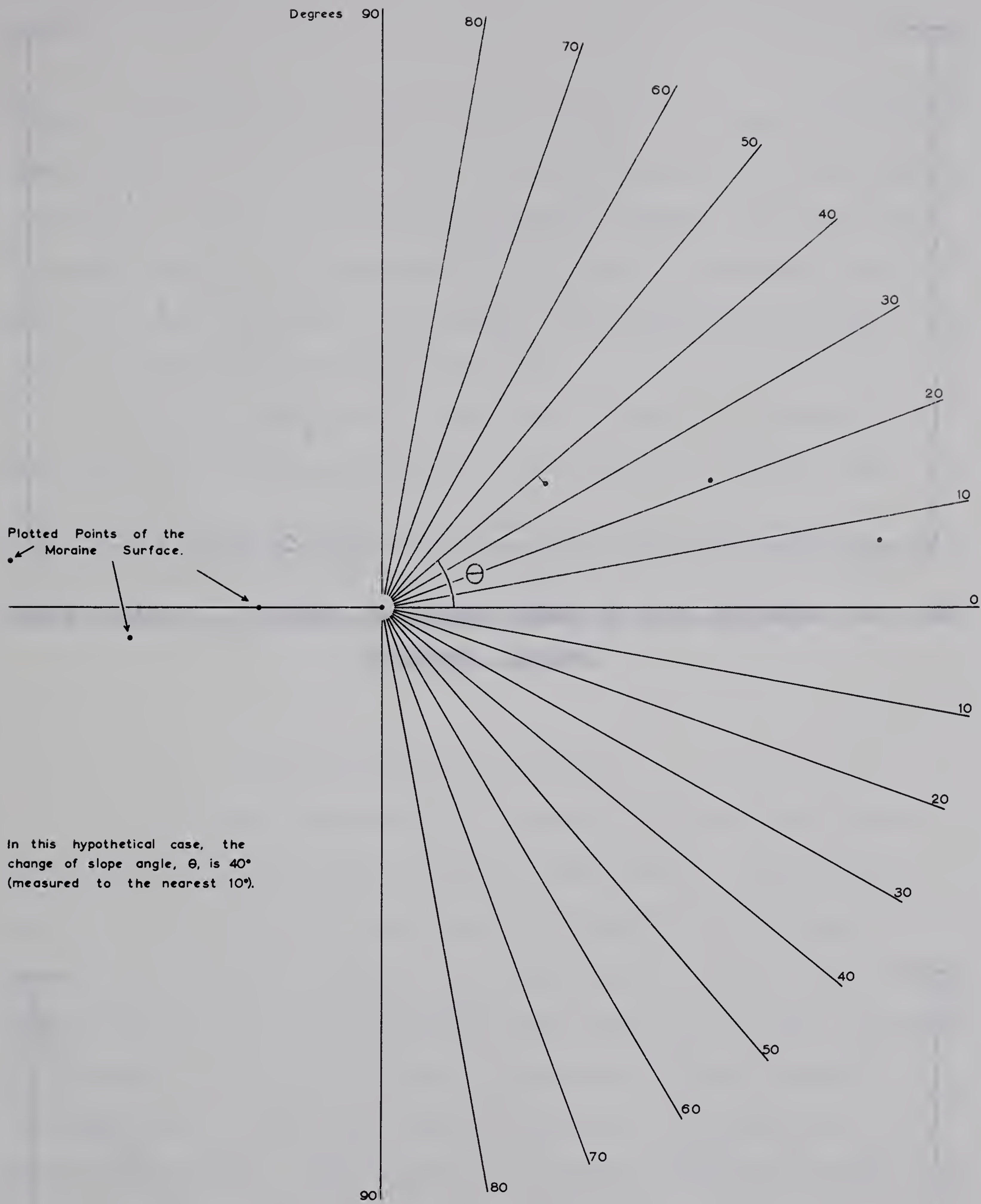


Figure 28: Guide Line Pattern for the Measurement of θ.

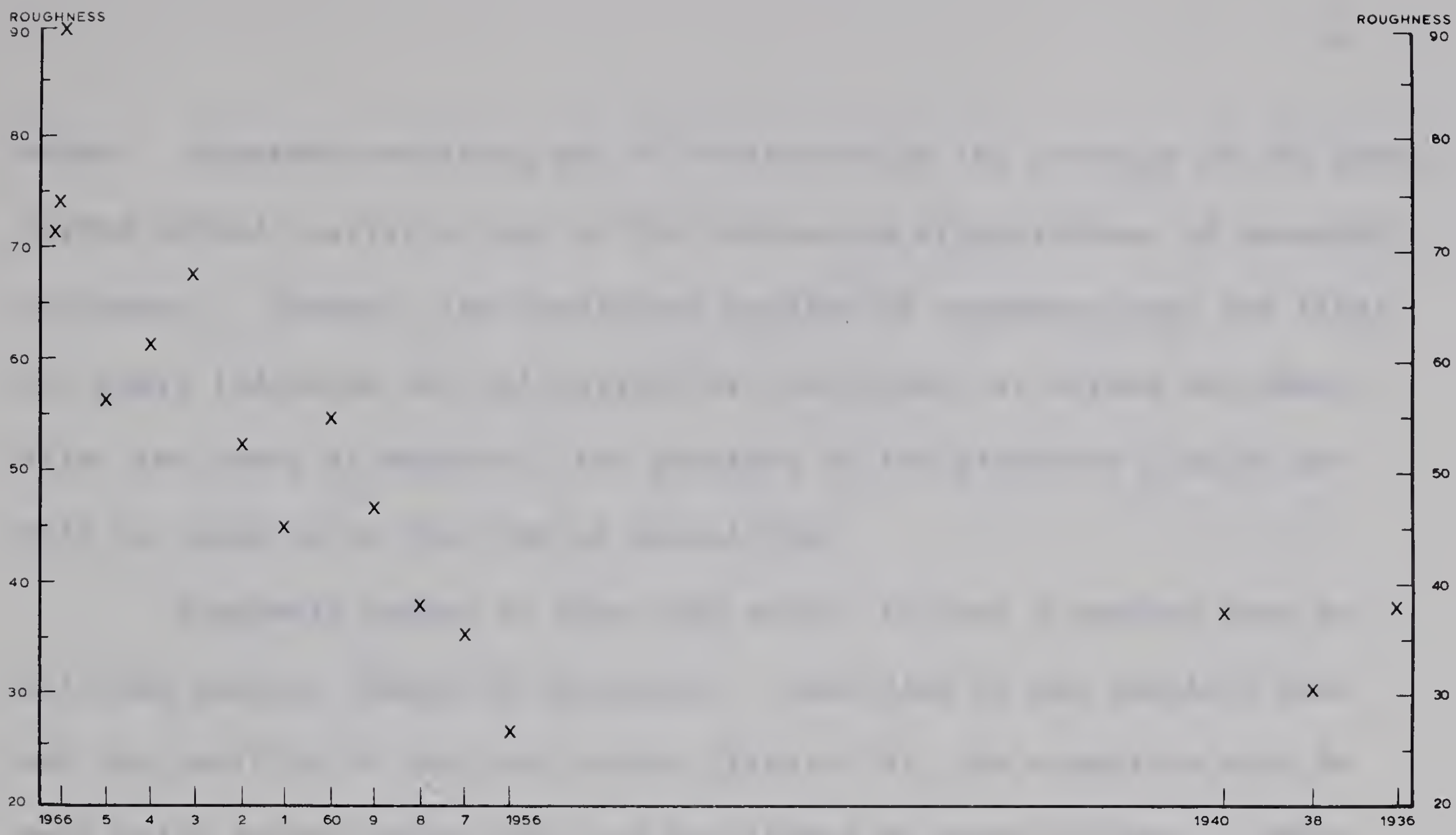


Figure 29(a): Actual Roughness Values on the Moraines of the Athabaska Glacier.

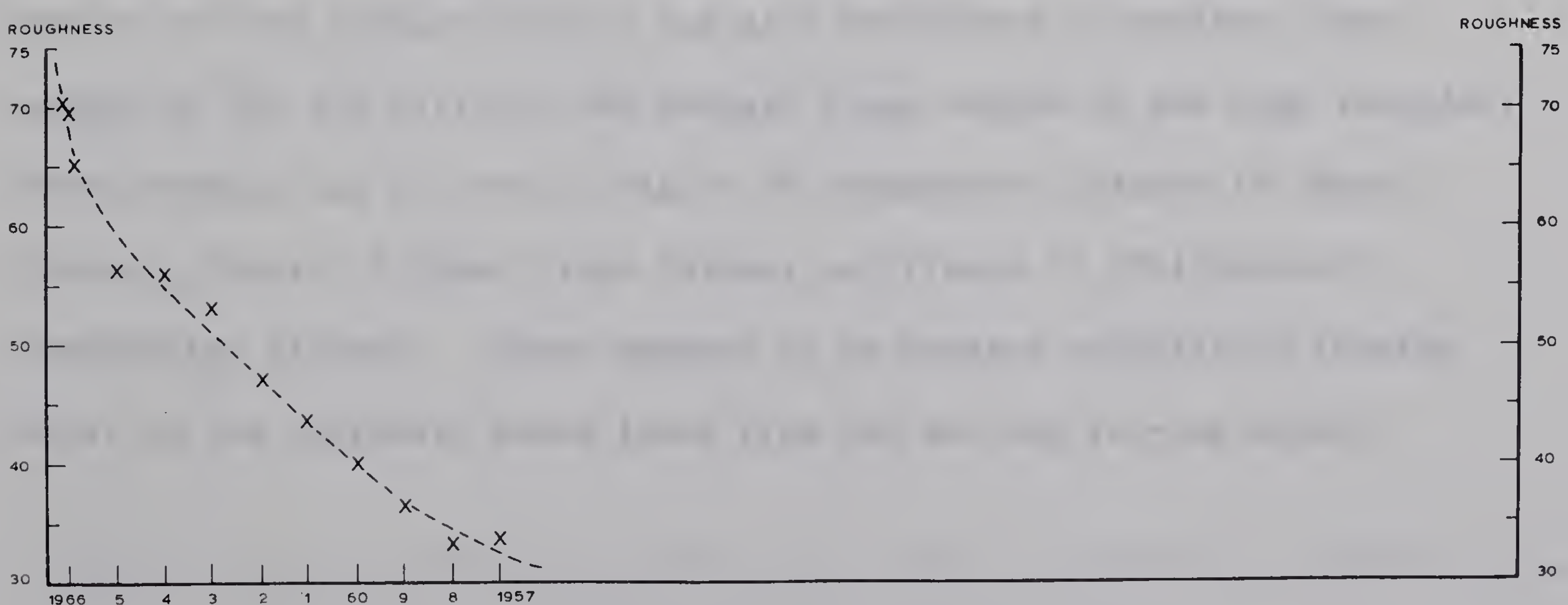
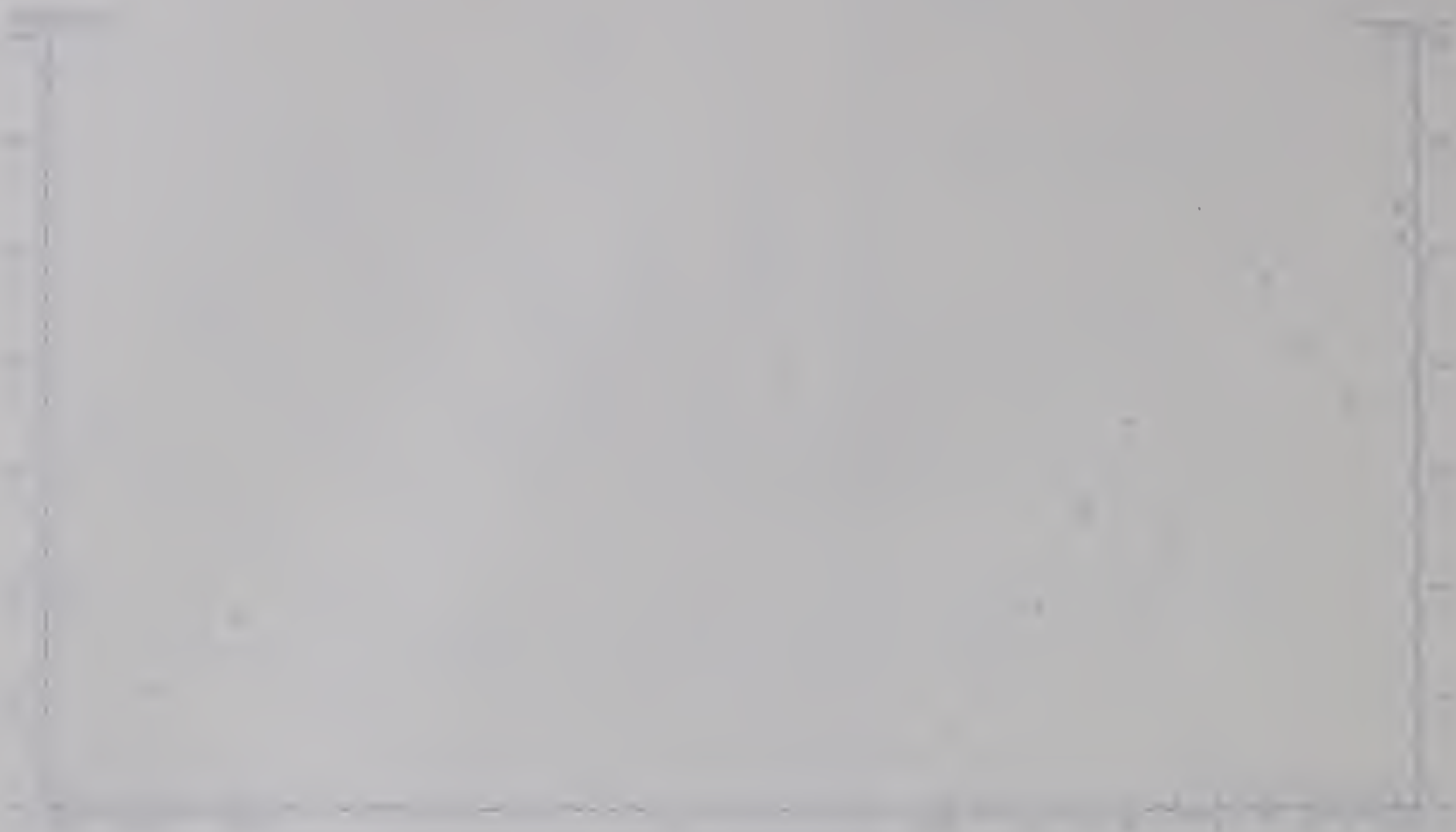
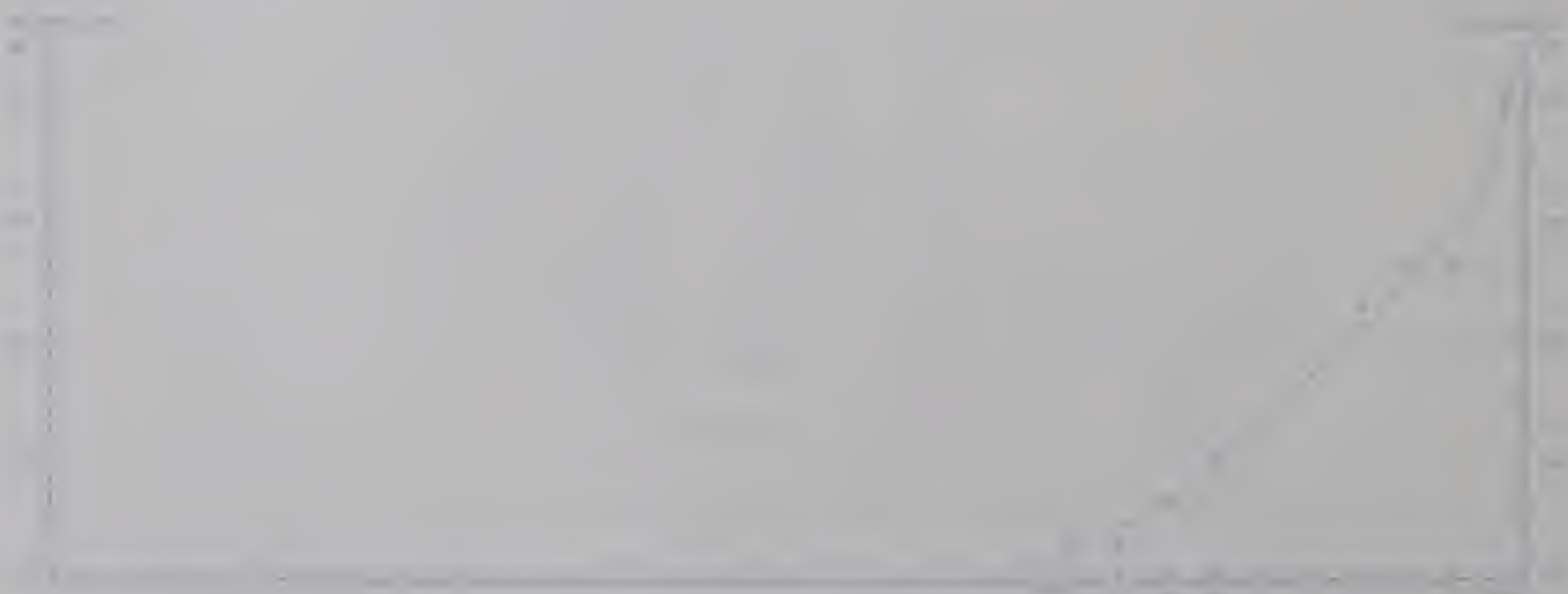


Figure 29 (b): Five Year Running Means of Roughness Values.





means. Apparent smoothing may be restricted by the accuracy of the Abney survey method, particle size or the decreasing effectiveness of geomorphic processes. However, the consistent decline of roughness over the first ten years indicates the reliability of the formula as worked out above. After ten years of exposure, the moraines of the Athabaska Glacier are half as rough as at the time of deposition.

Roughness cannot be less than zero: to have a moraine hump at all some angular change is necessary. According to the particle size and the position of the plot points (Figure 30), the asymptote must be some value greater than zero, and may indeed be nearer thirty. These reasons may account for the flattening trends on Figure 29.

Summary of Topographic Changes

At the time of deposition, the moraines of the Athabaska Glacier have rough surfaces and a wide variety of slope angles. Through time, processes of frost action, running water and gravitational collapse smooth out the surface details and give preference to maximum slope angles in the low thirties and average slope angles in the high twenties. These changes can be seen in Figure 29 (Roughness), Figure 16 (Upper Limits), Figure 18 (Mean Slope Values) and Figure 17 (Chi-Squared Probability Values). There appears to be greater activity of running water on the northeast faces (away from the sun and ice-cap winds).

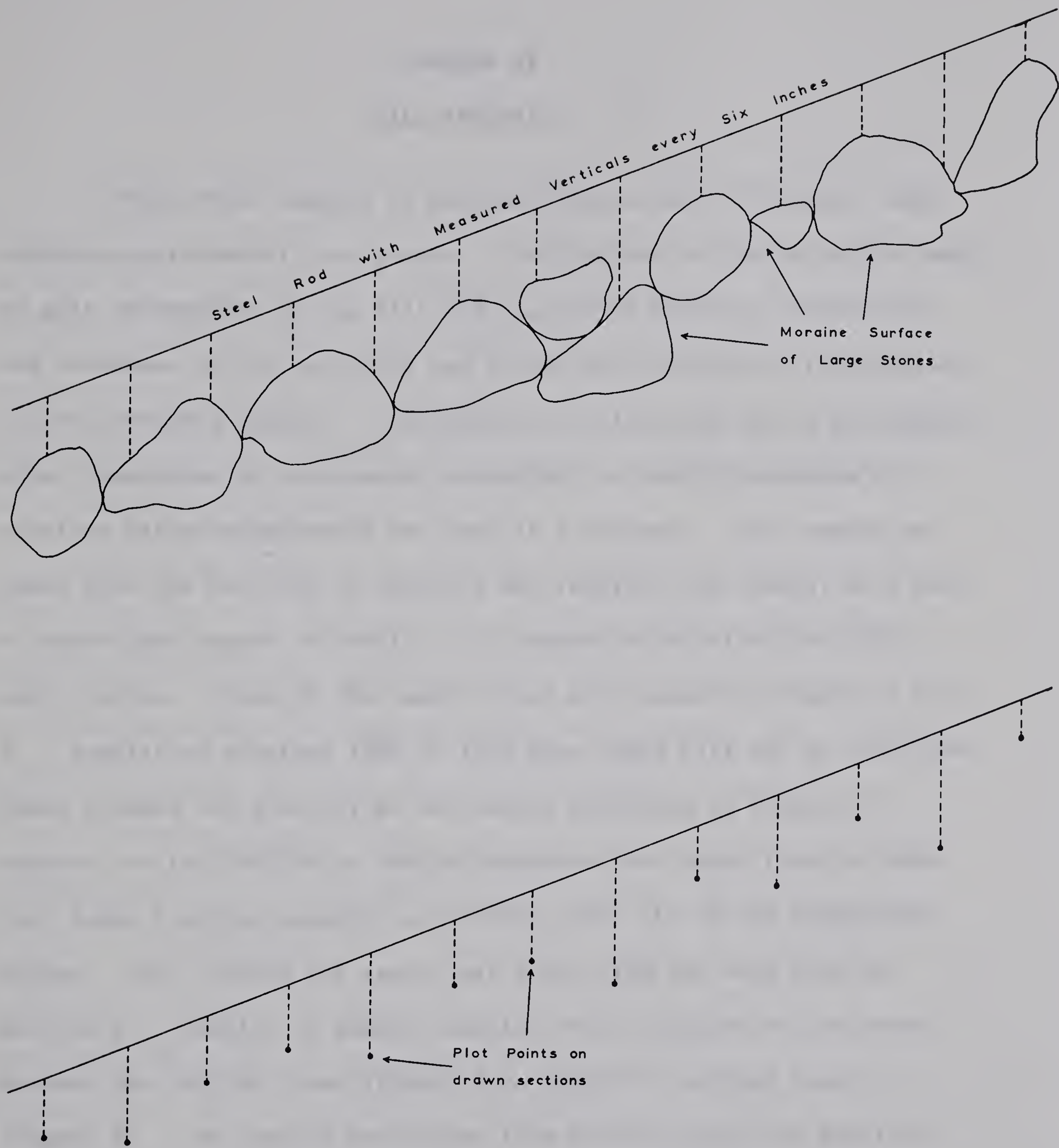


Figure 30: A Straight Slope of Large Material resulting in a "rough" surface when drawn.

CHAPTER IV

TILL ANALYSIS

Forty-three samples of glacial deposits were collected, each weighing approximately ten pounds. The purpose of the collection was to gain information on the silt and clay sized fraction, sphericity and roundness of the particles and stones that constitute the moraines of the Athabaska Glacier. The period of collection was in mid August, after completion of topographic surveying, so that disturbance of moraines before measurement was kept at a minimum. Each sample was taken from the top inch of deposits and required the removal of a six or seven inch square of debris, i.e. between thirty-five and fifty cubic inches. Most of the sample sites are located on Figures 8 and 9. Samples on moraines 1880 to 1942 were taken half way up the front faces (toward the glacier) at the points indicated on Figure 8. Samples for the 1955/56 to 1964/65 moraines were taken from the back face (away from the glacier) of section lines 'A' of the respective ridges. For 1965/66 the sample was taken from the back face of Section G. Samples of summer deposits were collected in the areas between the 1965/66 G and 1964/65 A to 1955/56 A section lines (Figure 9). No samples were taken from between the older moraines since those areas have been much affected by running water. Water sorting and redepositing of debris is common and samples would not be representative of the material as originally deposited by the Athabaska Glacier.

The recent samples (1955 to 1966 Summer) have been collected from as near a straight line as was possible. This line is at right angles to the front edge of the glacier and to the moraines, and therefore parallel to the direction of movement of the glacier. Where bedrock changes across the valley floor underneath a glacier, so too would the resulting drift trains change across the valley. The use of a sample line parallel to the flow of ice eliminates as far as possible differences in the original composition of the till.

Meltwater action has removed the eastern ends of the 1955/56 to 1965/66 moraines. At the eastern end of the 1964/65 moraine, four samples (1964/65 W to Z, Appendix E) were taken to obtain a more complete assessment of the moraine (Figure 31 and Plate 18). At the equivalent place on the 1962/63 moraine one sample, 1962/63 Z, was taken from the base (Figure 32). Where the recent annual recessional moraines are cut by the meltwater stream, a fifteen foot high section of till is exposed (Plate 19). One sample, 1955 Z, was taken at a depth of four and a half feet at the point indicated on Figure 9. This sample is located by the geological hammer on Plate 19. Three samples X to Z, were taken from the 1965/66 moraine between section lines A and F (Figure 9).

The material of the moraines of the last two decades is at least ninety-five percent black limestone. Occasional stones of sandstone and quartzite may be found. On the older moraines, material is about two-thirds sandstones, frequently containing a high iron content in the cement, the remainder being mainly of limestones, shales

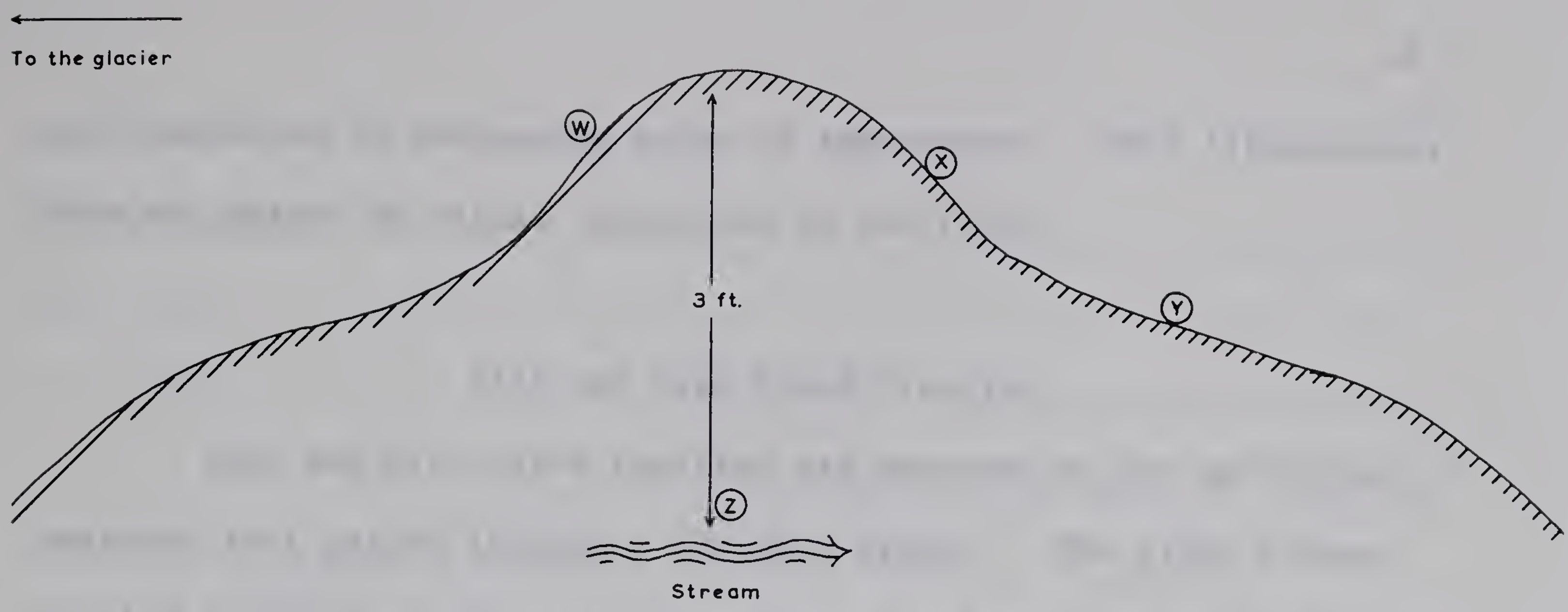


Figure 31: Positions of Samples W to Z at the East End of the 1964/65 Moraine of the Athabaska Glacier (See Plate 17).

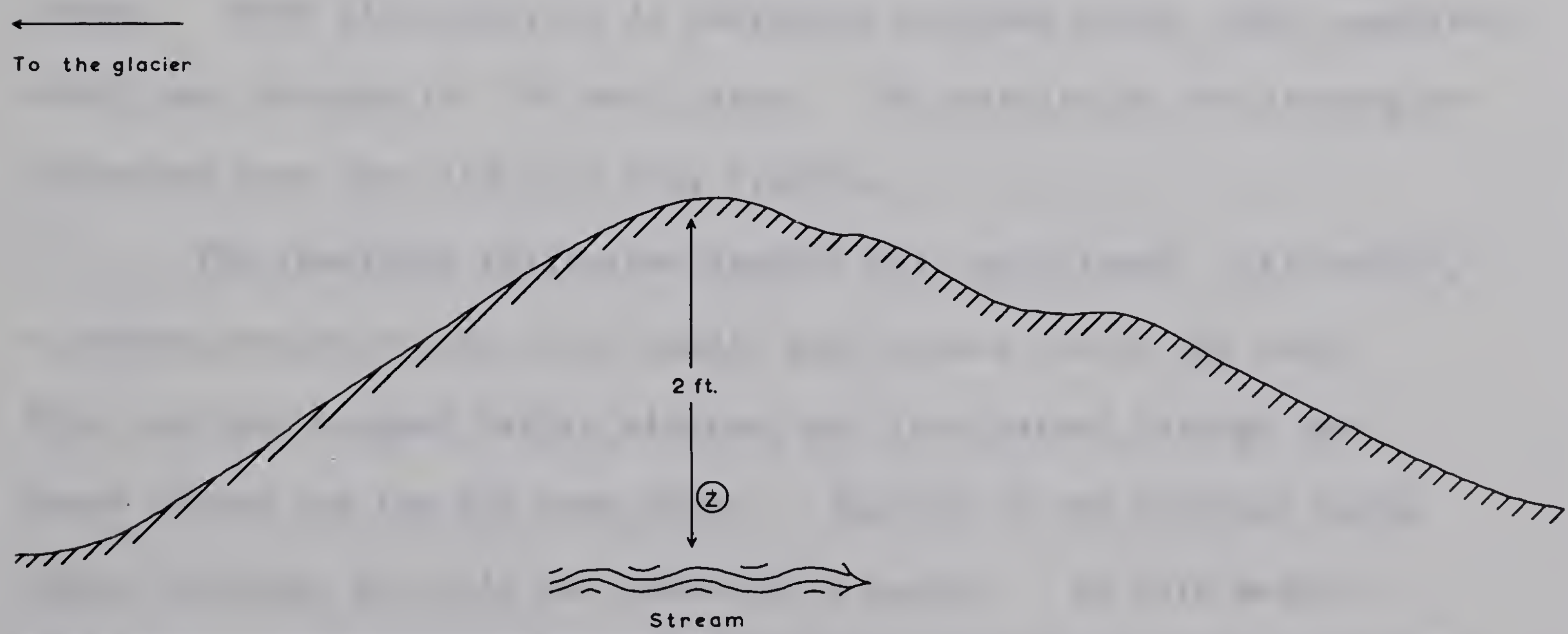


Figure 32: Position of Sample Z at the East End ot the 1962/63 Moraine of the Athabaska Glacier.

and quartzites in decreasing order of importance. This lithological data was gained by visual inspection in the field.

Silt and Clay Sized Fraction

Silt and clay sized fraction was measured by the percentage of material that passed through a 230 mesh sieve.[1] The first eleven samples studied were dry-sieved and gave clay fractions ranging between two and five percent. For this method a random portion of the sample was scooped out of the containing bag until a porcelein bowl was filled with approximately two to five hundred grammes of material. This material was then sieved through the 230 mesh, using two coarser sieves as guards to protect the delicate mesh from the large pebbles. The material retained by the three sieves and the material which passed through all three sieves were both weighed.

Unfortunately the results of this method are unreliable because the dry, finer particles tend to adhere together and to the larger stones. Much fine material is therefore retained which, when separated, would pass through the 230 mesh sieve. The results by dry-sieving are therefore less than the true clay fraction.

The remaining thirty-two samples were wet-sieved. As before, a random portion of the total sample was scooped out of the sack. This was then weighed before sieving, and then passed through two guard sieves and the 230 mesh sieve. Instead of dry material being shaken through, the till was washed by a spray. By this method

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1 Geological sieves are of two sets of wires crossing at right angles. A mesh size of 230 on the Wentworth Scale means that adjacent parallel wires are 0.0625 millimetres apart.

For the sake of brevity, silt and clay sized fraction will hereafter be referred to as clay fraction.

flocculation was prevented and all fine particles passed through the 230 mesh sieve. The portion retained on the three sieves was then dried and weighed together. By subtraction the total portion of fine particles could be calculated. The results, including percentages of clay, are presented in Appendix E and are plotted on Figures 33 and 34.

Figure 33, the graph of actual clay fraction values, shows a general decrease of clay percentage with the passage of time. This is especially true of the older moraines, 1940 to 1880. This result concurs with the field observation that rainwash removes fine particles from the surface over a period of time (Chapter 3).

The outstanding feature of Figure 33 is the generally lower values of clay fraction of deposits laid down during the recent summers. This tendency can be seen more clearly on Figure 34, five year running means for winters and summers respectively. Five year running means for winters are mostly between twenty-nine and forty percent; the equivalent values for summer deposits are between twenty and twenty-six percent. This difference in clay fraction is possible due to the fact that morainic ridges are above the level of the meltwater which issues from the glacier. Thus they are little affected by fluvial action over their surfaces. On the other hand, summer deposits form the ground over which meltwater flows for one or two years after deposition. During that time much fine material is carried away in suspension.

Subsurface samples (1964/65 Z, 1962/63 Z and 1955 Z) and other surface samples (1965/66 X and 1964/65 X) show no consistent variations

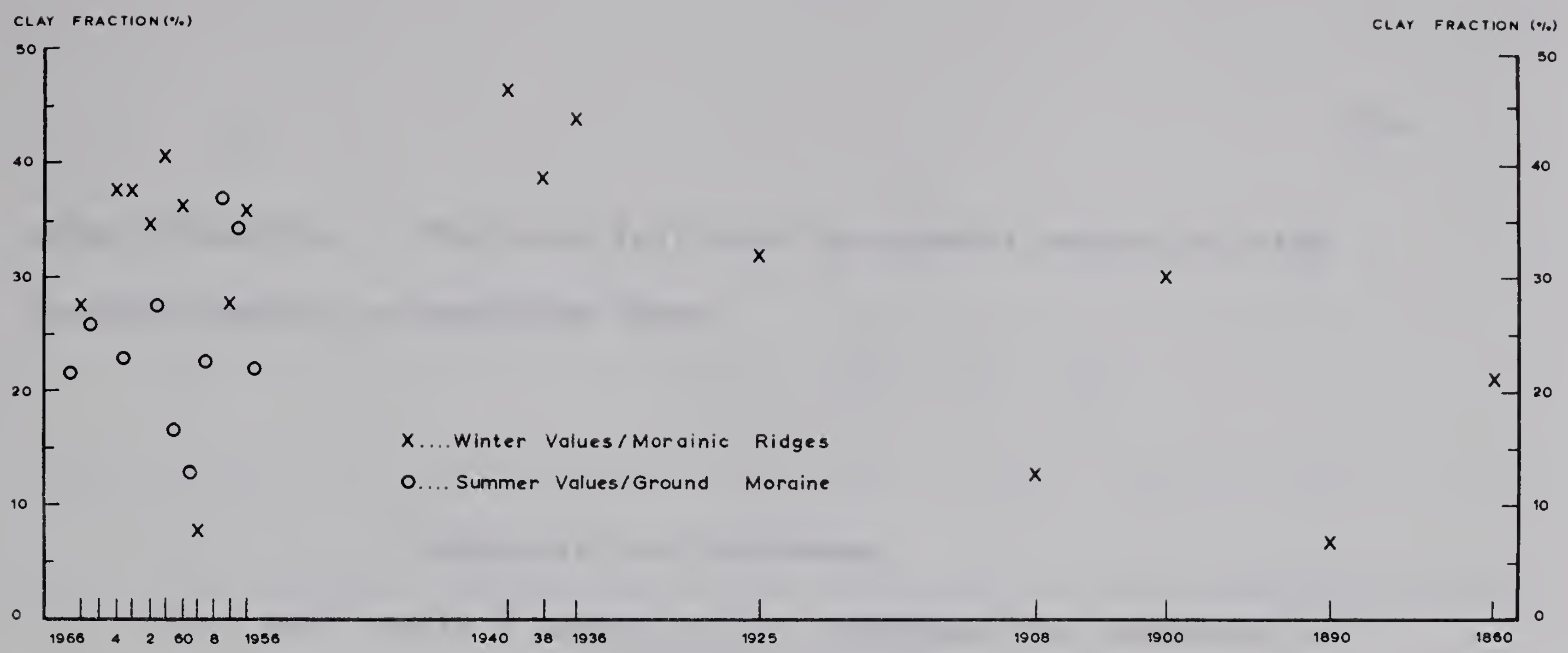


Figure 33: Actual Values of Clay Fraction of Till Samples from the Moraines of the Athabaska Glacier.

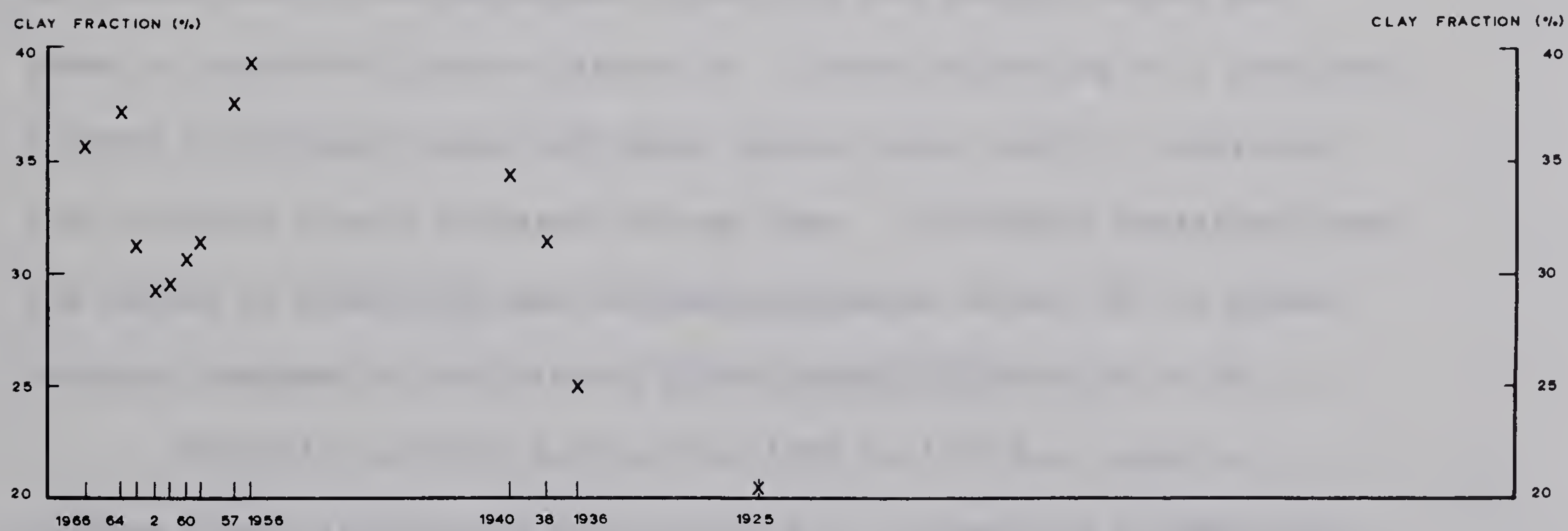


Figure 34 (a): Five Year Running Means of Winter Till Sample Clay Fractions from the Moraines of the Athabaska Glacier.

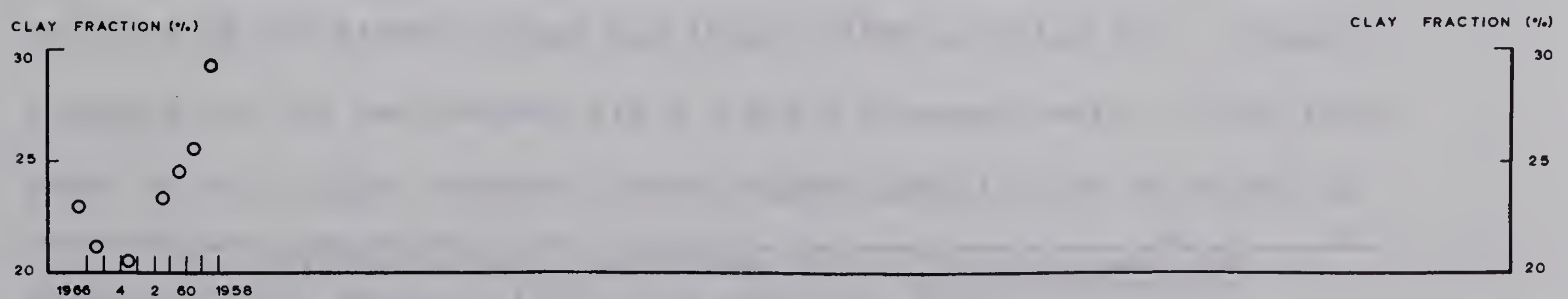
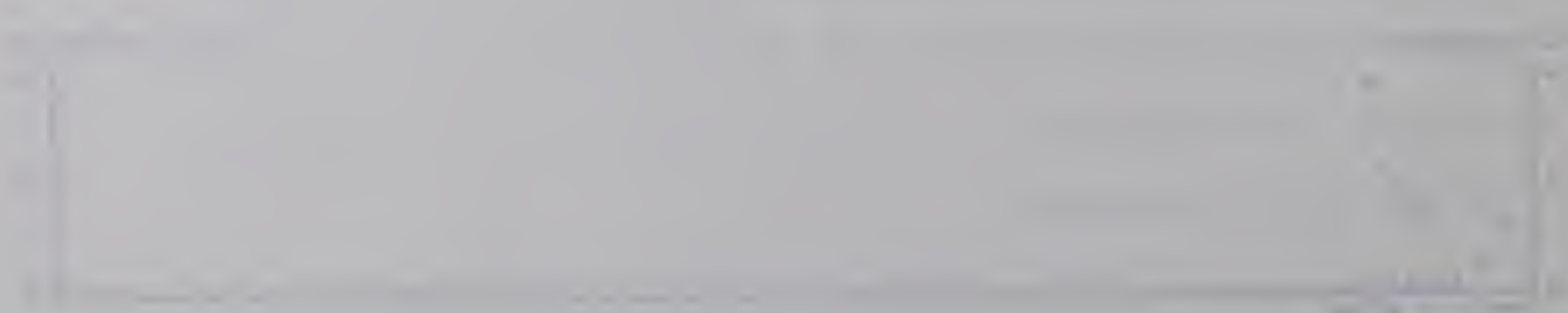


Figure 34 (b): Five Year Running Means of Summer Till Sample Clay Fractions.



among themselves. They also fall into the general pattern of clay fraction results as described above.

Sphericity and Roundness

For each sample a measure of the roundness and sphericity of stones was obtained. The complete sample was passed through a sieve of five-eight's inch square mesh. The stones which were held by the sieve, usually between twenty and fifty in number (Appendix E), were compared visually with roundness and sphericity charts.[2] The number of stones used, their aggregate sphericity and average values are shown in Appendix E and on Figure 35. Since weathering is a continuous process and exposed faces and edges weather more readily, sphericity and roundness should increase through time. One would therefore expect the trends of sphericity and roundness (Figures 35 and 36) to appear reversed compared to the various slope graphs (Figures 14 to 24).

Morainic material dating from 1966 to 1955 has stones of average sphericity ranging from 5.8 to 4.5. From 1942 to 1880 the equivalent values are from 5.8 to 4.9. Of the thirty-two values ascertained from the more recent deposits, ten are of 5.0 or less.[3] Only one of the eleven values for 1942 to 1880 is below 5.1. Overall averages for the two periods are 5.2 and 5.4 respectively. Thus there seems to be a slight tendency toward higher sphericities of stones on

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2 Krumbein, W.C., and Sloss, L.L., "Stratigraphy and Sedimentation", Freeman, 1963, (2nd Edition), p.111.

3 No significance is attached to the value of 5.0.

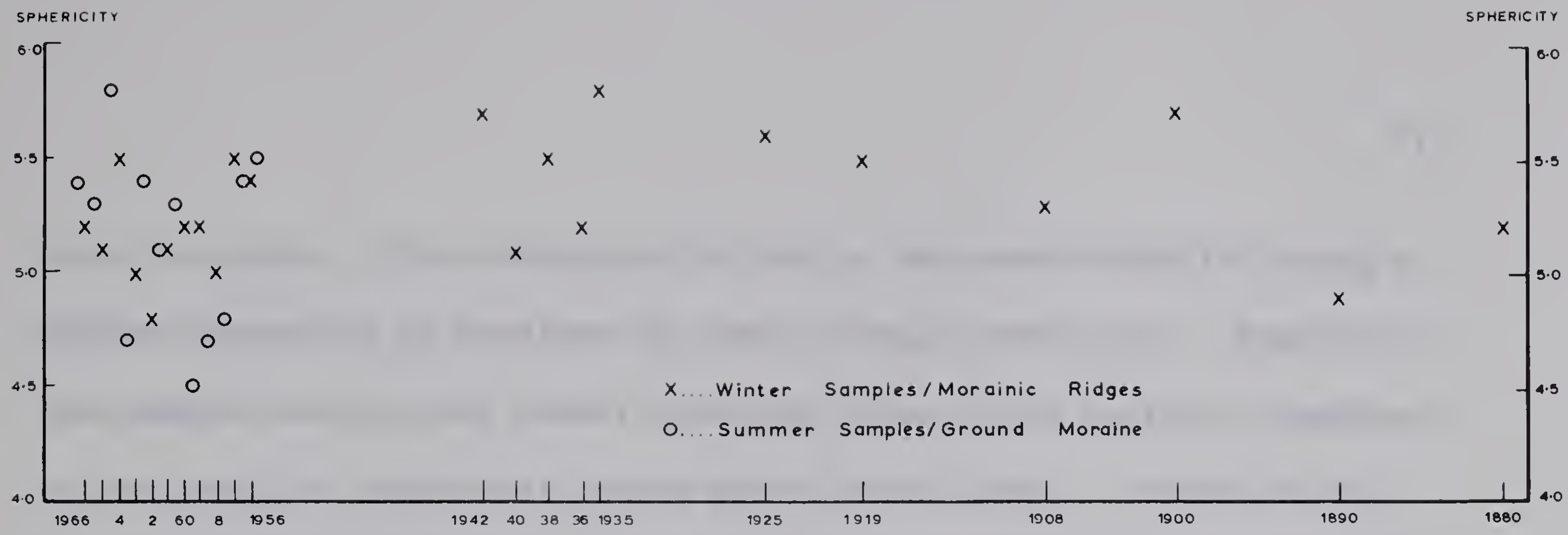

Figure 35: Actual Values of Stone Sphericity of the Moraines of the Athabaska Glacier.

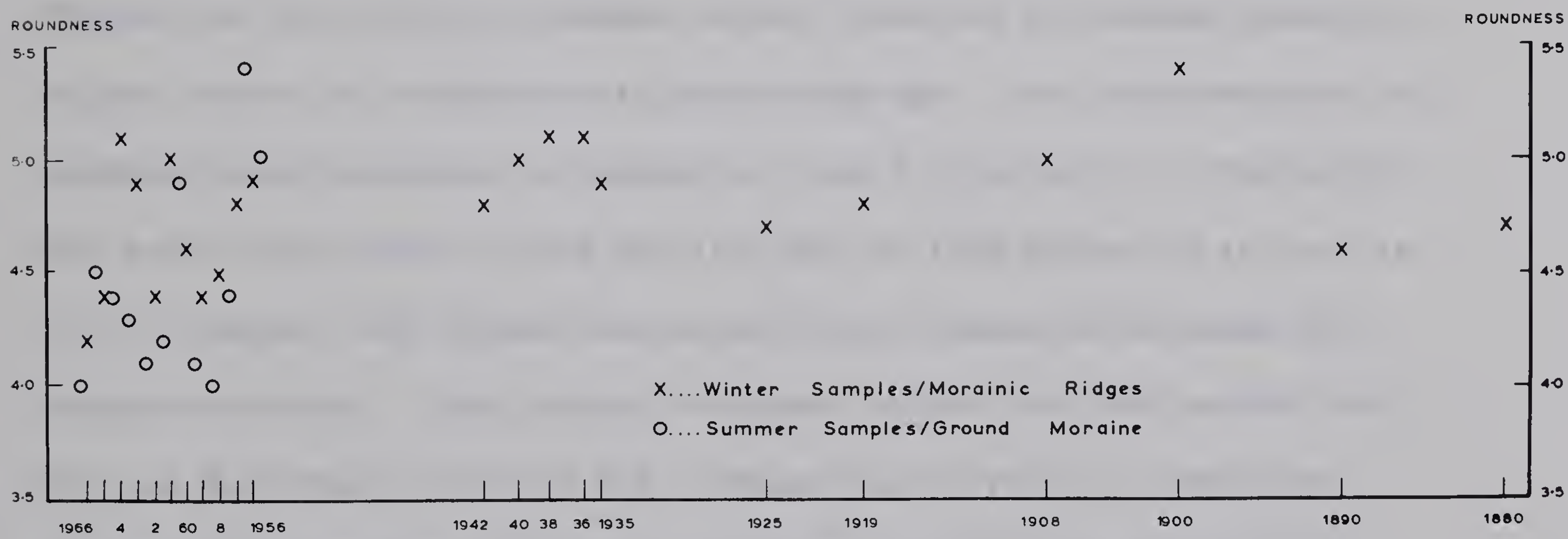

Figure 36 (a): Actual Values of Stone Roundness of the Moraines of the Athabaska Glacier.

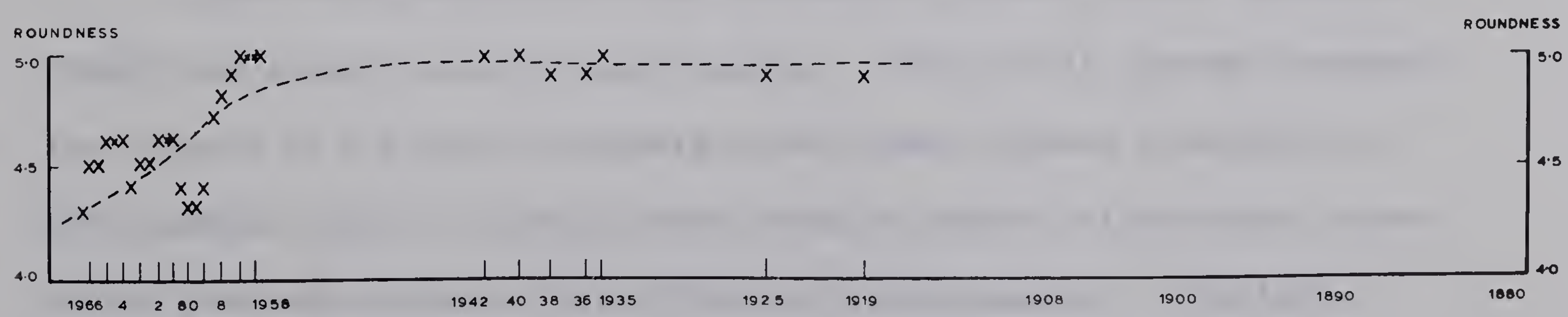

Figure 36 (b): Five Year Running Means of Stone Roundness.

older moraines. The difference is due to the newer deposits having a higher proportion of moraines of lower average sphericity. However, the sample averages and overall averages show little variation compared to the range of individual stones within each sample. There are no consistent variations among the other surface and subsurface samples compared to those taken along the main sampling line (Appendix E).

Roundness, which measures the smoothness of stones, was measured in the same manner and at the same time as sphericity. Data are presented in Appendix E. Again, there are no consistent variations according to depth or displacement from the main line of samples. Figure 36a, all actual roundness values, shows an increasing trend for higher values of roundness with increasing age. For most moraines the average stone roundness is between 4.5 and 5.1 inclusive. One value for each of the 1966 to 1955 and the 1942 to 1880 groups is as much as 5.4. However, all values less than 5.1 are concentrated among the younger moraines. The average roundness values for 1966 to 1955 is 4.5 and for 1942 to 1880 is 4.9. There is, therefore, a definite tendency for roundness values to increase through time (Figure 36b, all values averaged into five year running means).[4]

Even more important is the difference between winter (morainic ridge) and summer (intermoraine) values. The overall average roundness for summers is 4.4 and for winters is 4.7 (both figures from 1955 to 1966 samples only). In only three cases do summer values exceed those of the preceeding winter (1965, 1960 and 1956 summers). Similarly, only three summer roundness values exceed those of succeeding winters (1965, 1956 and 1955 summers).

4 No categoric correlation between increasing age and increasing roundness can be obtained from this data.

Winter deposits are elevated above the general level of terrain. Because of this increased exposure, they become more prone to temperature changes than the ground around them. Furthermore, the summer deposits are usually saturated by meltwater for a year or two after deposition. The large amount of water present tends to delay freezing and consequently reduces the action of frost. Stones in the morainic ridges are therefore more susceptible to mechanical reduction and the removal of surface irregularities.

The increased roundness of stones in winter deposits may alternatively be related to the nature of origin of these ridges. The pushing action of the glacier in forming the annual recessional moraines would tend to exert additional abrasive force on the pebbles of the ridges compared to the areas between, and thereby reduce their roughness. Although both operations possibly account for the differences in roundness, the latter explanation seems more probable. The relative action of frost as described above is only hypothesized, whereas winter advance must occur to create the morainic ridges.

In her work of 1945, Anastasia van Burkalow used wooden blocks of increasingly bevelled corners to study the effects of increasing sphericity on angles of repose in loose material.[5] She also studied changes of roundness by using sand groups of equal size but different roughness. Van Burkalow interchanged "angularity" and "roughness" as opposites for sphericity and roundness (increases of the former being

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5 Van Burkalow, A., "Angle of Repose and Angle of Sliding Friction, an Experimental Study." Geol. Soc. Am. Bull., Vol.56, (June 1945). pp. 669 - 708.

measured as decreases of the latter). Slope angles were found to vary directly with angularity and roughness of pebbles.

This study agrees with the findings of van Burkalow. Mean slope angles on the moraines of the Athabaska Glacier show decrease and mean sphericity and roundness values of till samples show increase through time. Although the net changesare relatively small, in all three parameters the changes are rapid at first and slower thereafter.

Van Burkalow also showed experimentally that slope angle varies inversely with fragment size in perfectly sorted materials but directly in those imperfectly sorted. Increases or decreases of clay fraction will respectively decrease or increase the average particle size in imperfectly sorted materials. The loss of fine particles through time therefore increases the average particle size of the remainder. In this interpretation there is disagreement with the work of van Burkalow. Alternatively, reduced cohesion caused by the loss of clays may be more important than the effect on average particle size.

However, the loss of fine particles also increases the degree of sorting, so that over a period of time, the surface till on the slopes of the moraines of the Athabaska Glacier becomes better sorted. Therefore, in another sense, this study at least does not disagree with van Burkalow.

Although changes of clay fraction, sphericity and roundness are statistically small, they do illustrate general agreement with previous work. The analysis of till samples confirms the visual impressions gained in the field. These are that processes of surface rainwash

remove finer particles, presumably by lubrication and by rolling down the slopes, and that weathering smoothens and rounds the stones. These changes in the till show that geomorphic processes do not change slope characteristics without having some effect on the material. It is indeed possible that the processes work through changes of the till.

CHAPTER V

CONCLUSIONS

The results of this thesis stand as an example of the evolution of recessional moraines, consisting of loose, unsorted debris, under periglacial conditions. However, no extrapolation can be made as to the evolution of slopes under a fluvial cycle. In order that slope profiles could be compared on the basis of absolute dating, the study area was located on an area of recessional moraines. These slopes were not formed under the action of running water, a process which is only partly responsible for their later evolution. A direct comparison with the work of Savigear[1] and Young[2] is therefore not possible.

A second shortcoming is that different methods of survey were used for the recent and the older moraines according to their relative sizes. Brunton compass measurements are thought to exceed Abney level traverse slope measurements for any given facet by two or three degrees. The maximum error of the Abney level method is plus or minus three degrees and of the Brunton compass method plus or minus one half of a degree (Pages 17 to 20). It is therefore possible, though unlikely, that slope measurements by each method could diverge by as much as six or seven degrees. This is the greatest amount by which

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1 Savigear, R.A.G., "Some Observations on Slope Development in South Wales," Trans. Inst. British Geographers (1952), No. 18, pp. 31 - 52.

2 Young, A., "Some Field Observations of Slope Form and Regolith, and their Relation to Slope Development," Trans. Inst. British Geographers (June 1963), No. 32, pp. 1 - 39.

Brunton measurements could exceed Abney measurements, but since the operative errors have both positive and negative sign, the Abney measurements could theoretically exceed Brunton measurements by one half of a degree.

These differences, on average two or three degrees, may partly explain the reversal of trends as shown on the five year running mean graphs of Central Values, Upper Limits, Mean Slopes, Medians and Modes (Figures 15b, 16b, 18b, 19b, and 20b respectively). In order to equalize the measurement of all moraines, the older, larger moraines should be traversed in detail, although more elaborate equipment and a two-man team would be required for this work.

Despite these shortcomings, the availability of known time periods can give an indication of the decreasing rate of evolution as slope angles tend towards a new equilibrium with their environment. An expression of the changing rates of evolution of various morainal factors can be given by comparing the time periods before and after fifty percent of their development has taken place. The time period before such development may be referred to as the "half-life".[3] Because of the nature of development, the half-life is always less than the mid-point of the total period available.

The half-lives of various factors which are shown graphically in Chapter Three can be calculated in the same manner as the following example. The ranges of slope values (Figure 14a) vary from eighty degrees on the 1965/66 moraine to approximately ten degrees on the 1880

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3 "Half-life" as used here refers to changes which occur progressively more slowly, whereas radioactive nuclei decay at a constant rate. The expression "half-life" has been borrowed merely as a convenient term.

moraine (estimated to the nearest five degrees). The total variation is therefore seventy degrees, half of which is thirty-five degrees. This means that half of the change of range values has occurred when the range reaches forty-five degrees (thirty-five degrees plus ten degrees, the final value). Using the median guide line on Figure 14a, a range of forty-five degrees corresponds to a date of 1954. Thus the half-life of range values is twelve years.

Each property involves a different period of time, according to whether all moraines are used or only those traversed by Abney level section lines, and whether or not five year running means are calculated for either. The half-life is therefore better expressed as a percentage, so that different properties can be more easily compared. In the case of range of slope values, the total period of time involved is from 1966 to 1880, or eighty-six years. The half-life of twelve years becomes a percentage of approximately fourteen percent.

The calculations for range and for several other values are shown in Table IV. Many graphs show a reversal of trend, for example modes (Figure 20b, five year running means of modes). Other graphs trend from a wide to a narrow distribution (for example actual values of modes, Figure 20a). Half-lives for such cases have not been calculated since too many factors other than evolution due to subaerial processes enter the picture, especially where the change of trend corresponds to the change from recent annual recessional moraines to the older and larger moraines.

Table IV--Calculations of Half-Lives of Various Morainal Slope Features

Property	Variation (V)	Half V	Mid Point	Period (years)	Half Life	Percentage
Actual Range (Figure 14a)	80 to 10=70	35	45≡1954	1966 to 1880=86	12	$\frac{12}{86}$x100=13.95%
Five Year Running Means of Range (Figure 14b)	65 to 15=50	25	40≡1961/62	'66 to '19=47	4	$\frac{4}{47}$x100= 8.51%
Central Values (Figure 15a)	40 to 25=15	7½	32½≡60/61	'66 to 1880=86	5	$\frac{5}{86}$x100= 5.82%
Roughness (Figure 29a)	90 to 35=55	27½	62½≡62/63	'66 to '36=30	3	$\frac{3}{30}$x100=10.00%
Five Year Running Means of Roughness (Figure 29b)	70 to 35=35	17½	52½≡62/63	'66 to '57=10	3	$\frac{3}{10}$ x100=30.00%
Upper Limits (Figure 16a)	80 to 30=50	25	55≡1959/60	'66 to 1880=86	6	$\frac{6}{86}$x100= 6.99%

Of the six half-lives worked out in Table IV, five are less than fifteen percent. Central values reach half way to their final level within the first six percent of the total period of development, or five years out of eighty-six years respectively. The longest half-life, that of five year running means of surface roughness, is thirty percent. This figure is high due to the short period involved in the calculation of roughness, the fourteen years of Abney level sections, and the further shortening due to the use of five year means, making a total period of only ten years.

The availability of absolute dates therefore gives an indication of the changing rates of development of various aspects of the recessional moraines of the Athabaska Glacier. In general there is as much change in the first ten percent of the period of development as in the last ninety percent. That is to say, initial changes are generally ten times as rapid as later developments. The same relationship can be seen visually from the respective graphs (Chapter 3) of those factors not worked out numerically in Table IV.

The evolution of the moraines has been summarized in detail in Chapter Three, pages 32 to 35, 41 and 42, and 45. Briefly, the moraines are initially ridges of loosely piled till and intersticial ice. The surfaces are irregular and show no characteristic slope angle. Frost-heave and the melting of intersticial ice lead eventually to settling and slumping of the till and to preferred slope angles between twenty-five and thirty degrees. During the same time the moraine surfaces become smoother as a result of rainwash.

The geological parameters measured, clay fraction, sphericity and roundness, show little variation with time. At least in respect of those factors the geomorphic processes, outlined in Table III, act directly in changing surface characteristics, rather than by affecting the till.

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APPENDICES

APPENDIX A

Part 1

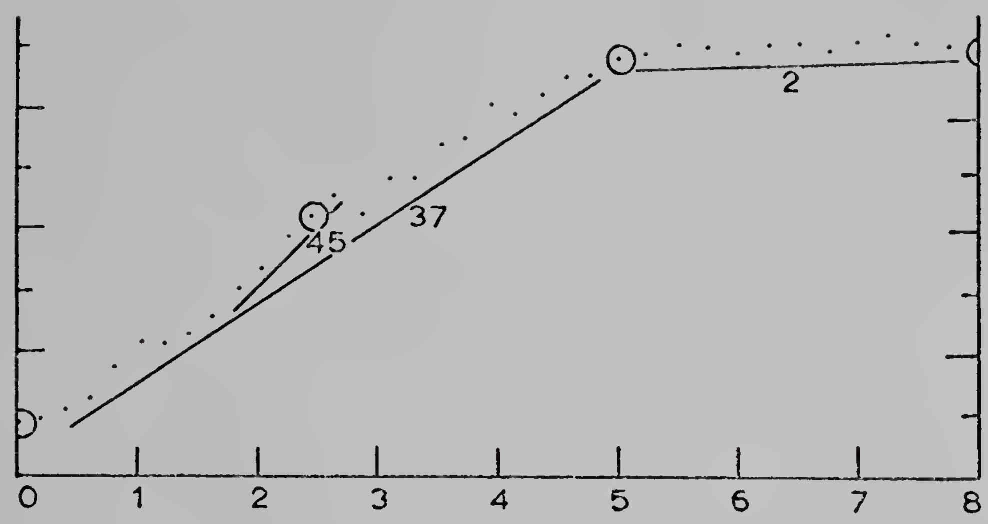
Abney Level Sections

The following pages contain the Abney level sections. These are reproduced at the scale of drawing. The reader can therefore check the author's interpretation of slope values against his own.

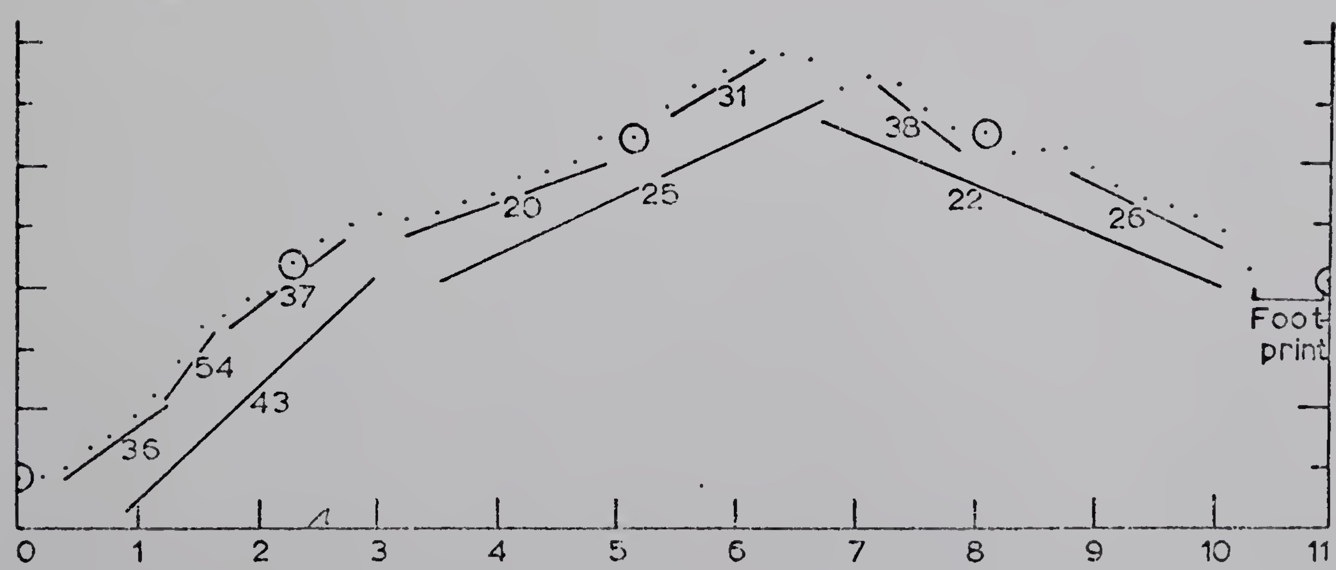
As a general rule the sections follow in increasing age (i.e. older dates), each page containing sections of similar date. Sections A to F of the 1965/66 moraine were surveyed three times during the summer of 1966 (mid June, mid July and mid August). The three surveys of each section are presented together so that topographic changes can be seen more easily by direct comparison. Sections G and H of the 1965/66 moraine were surveyed about two weeks after first exposure from melting snow, so that although measured after sections A to F, they are the "youngest" sections available.

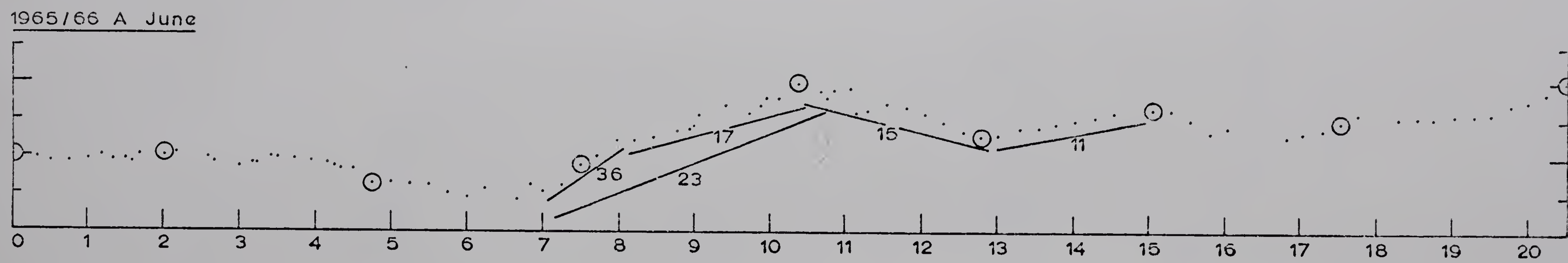
All the sections are at a scale of one millimetre to one inch. There is no vertical exaggeration. In all cases the right-hand side is toward the glacier.

1965/66 G



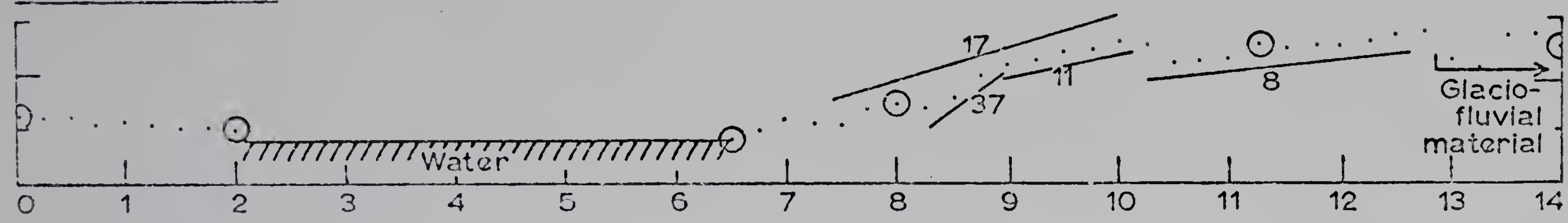
1965/66 H



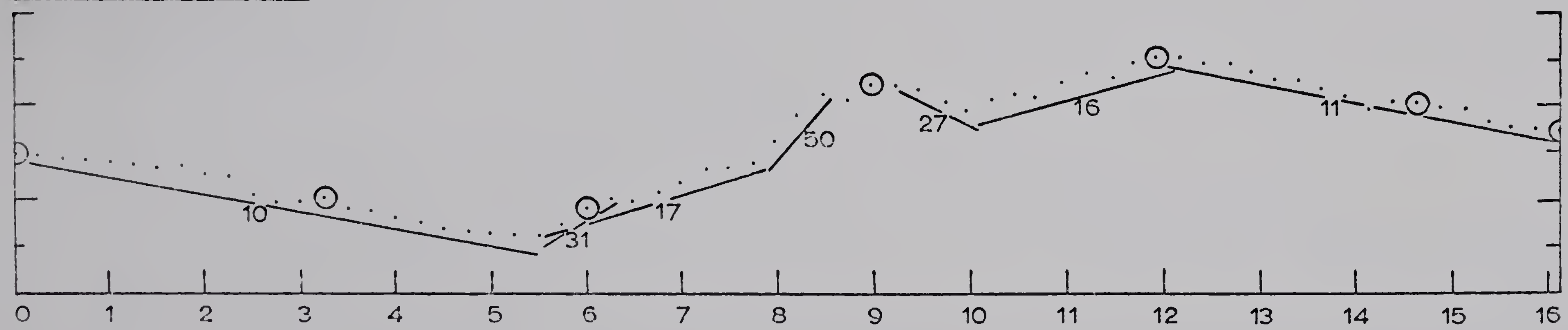


1965/66 A June
36
17
23
15
11
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

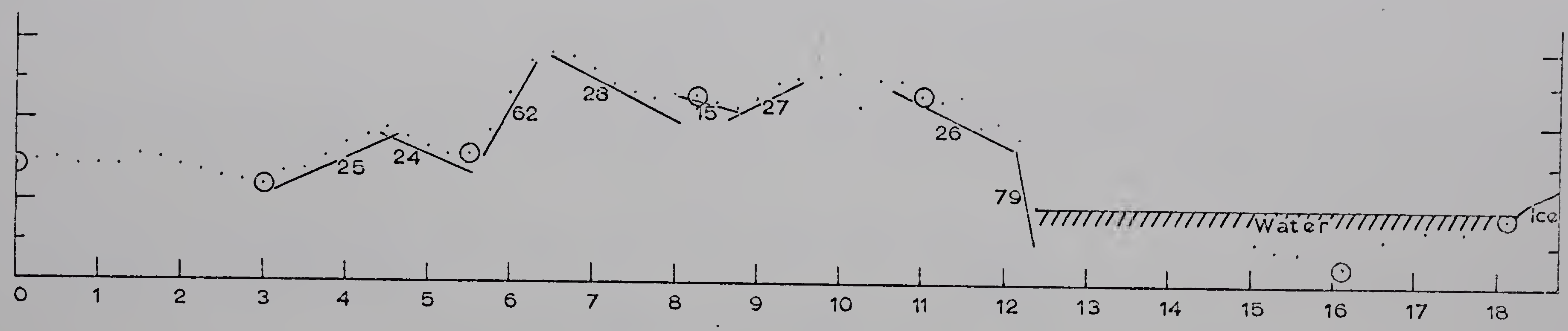
1965/66 A July



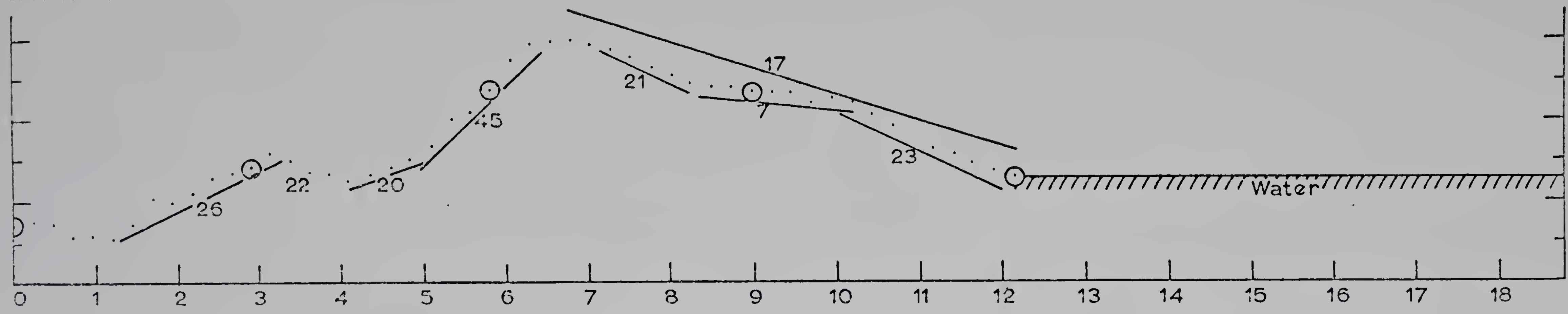
1965/66 A August



1965/66 B June



1965/66 B July



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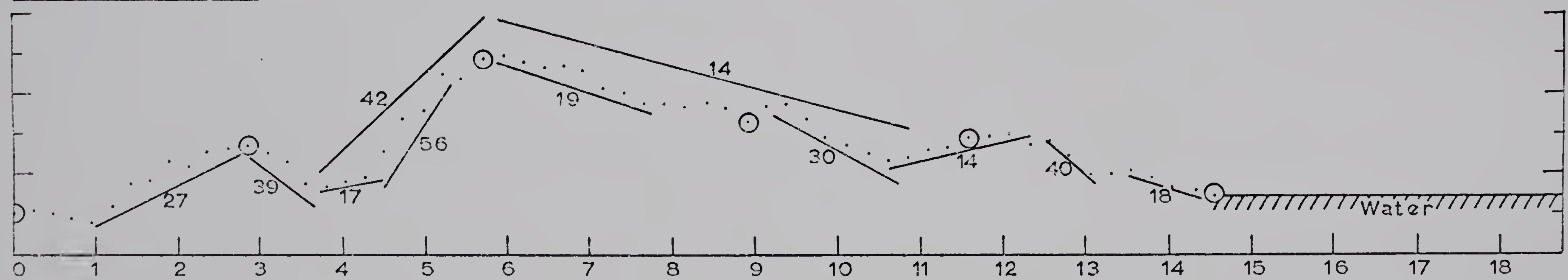
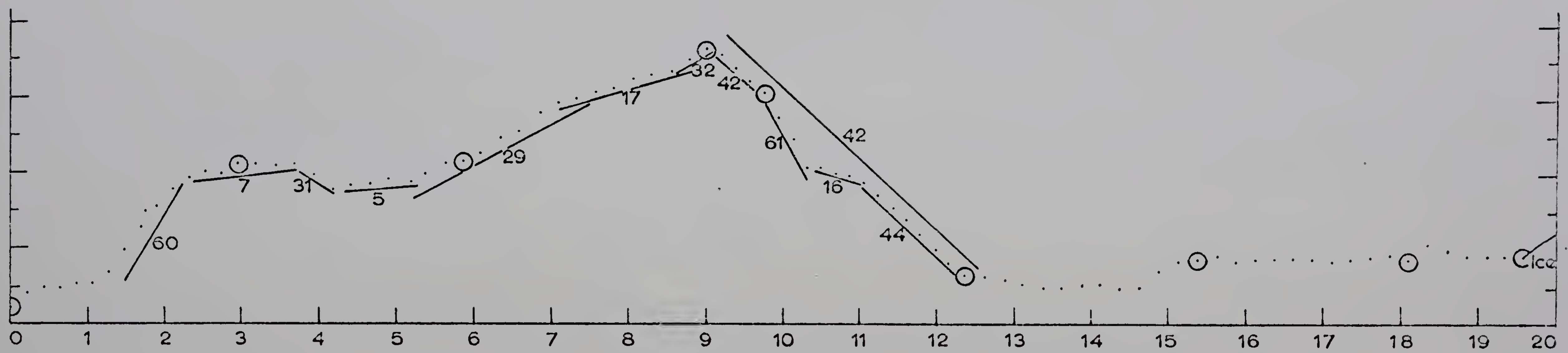


1965 / 66 C June



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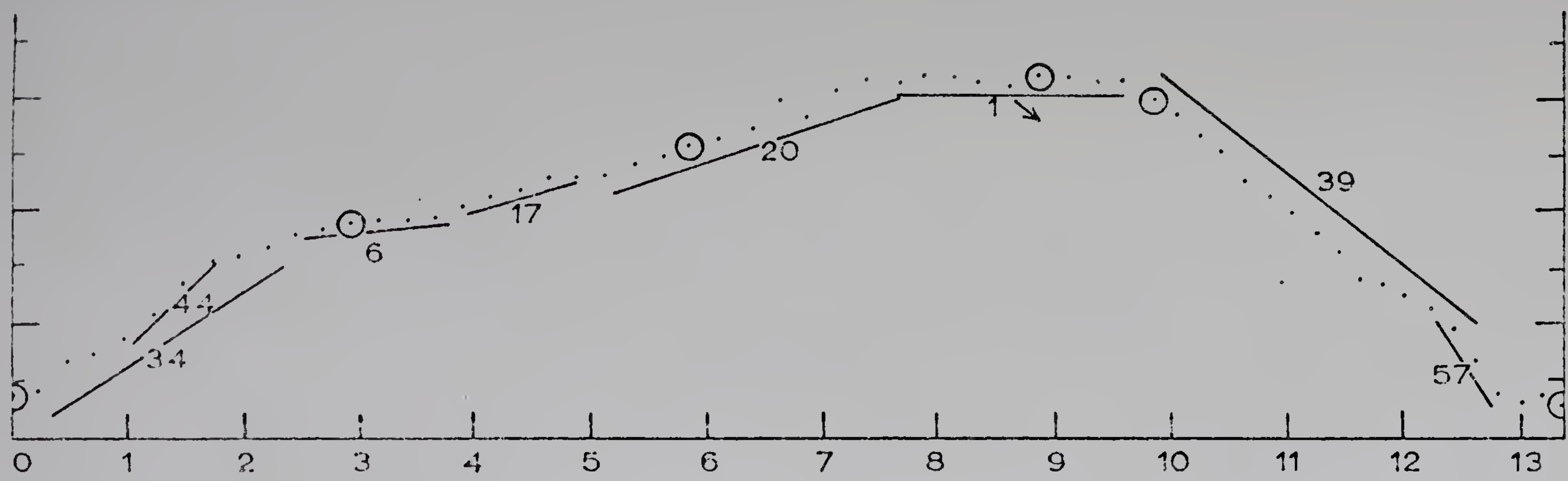

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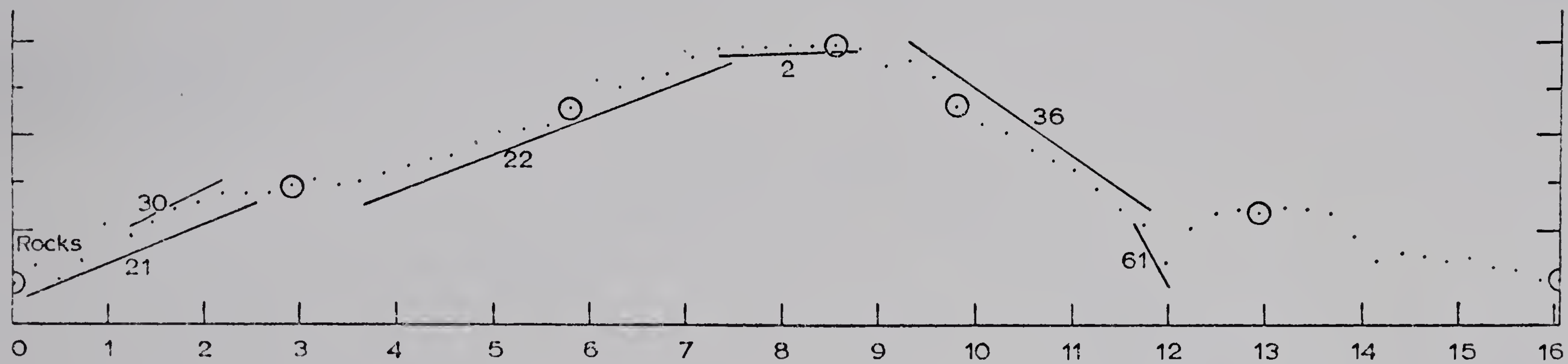

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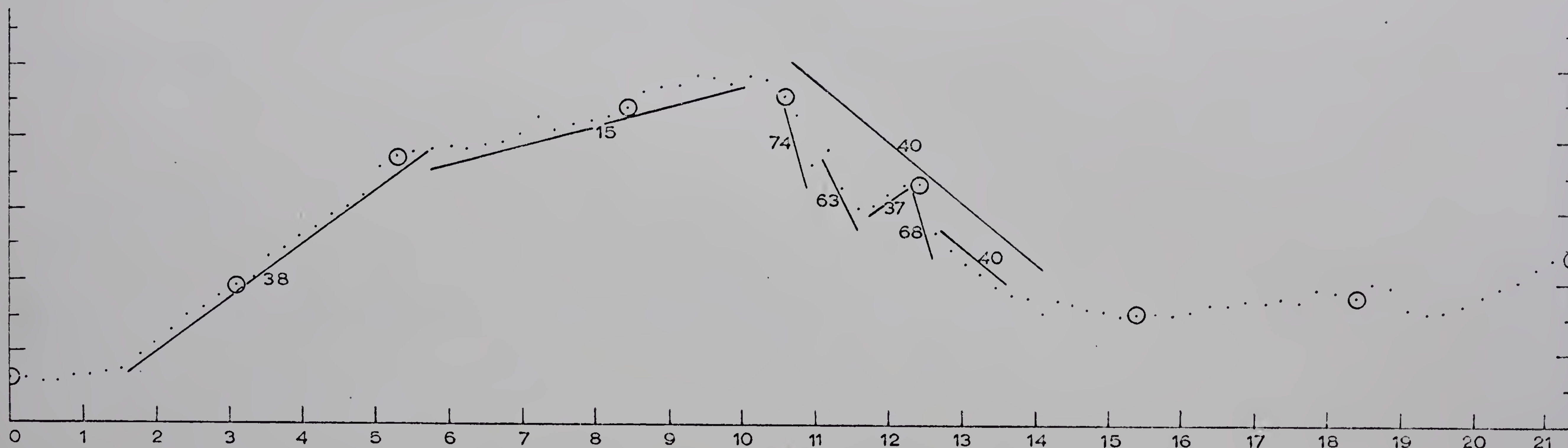

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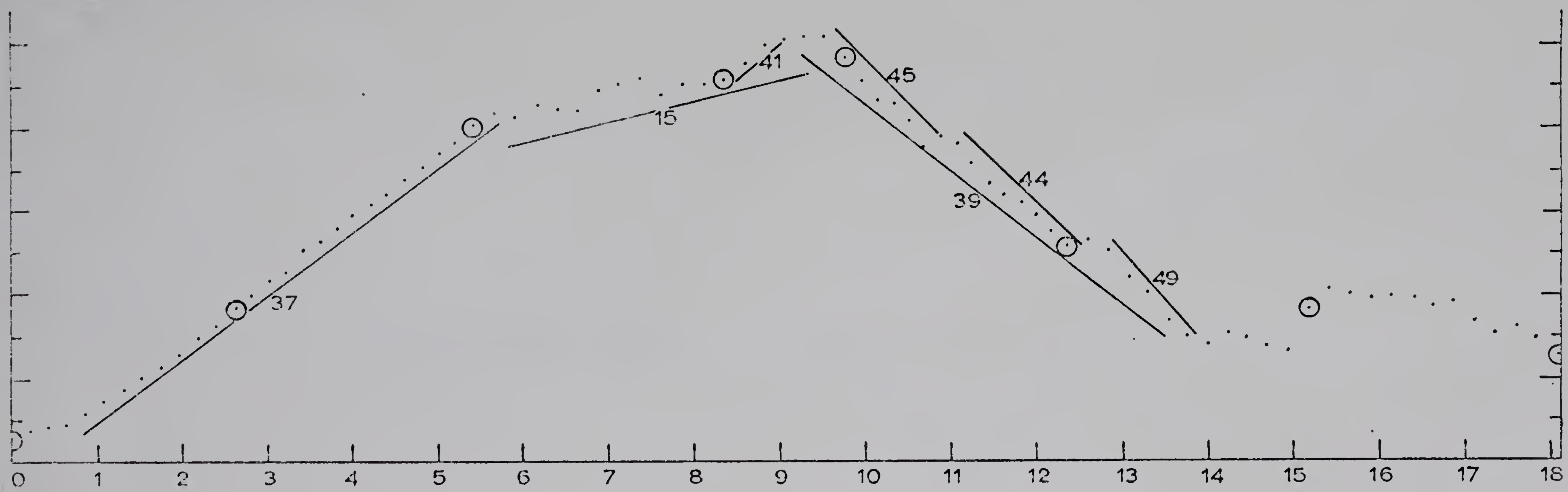

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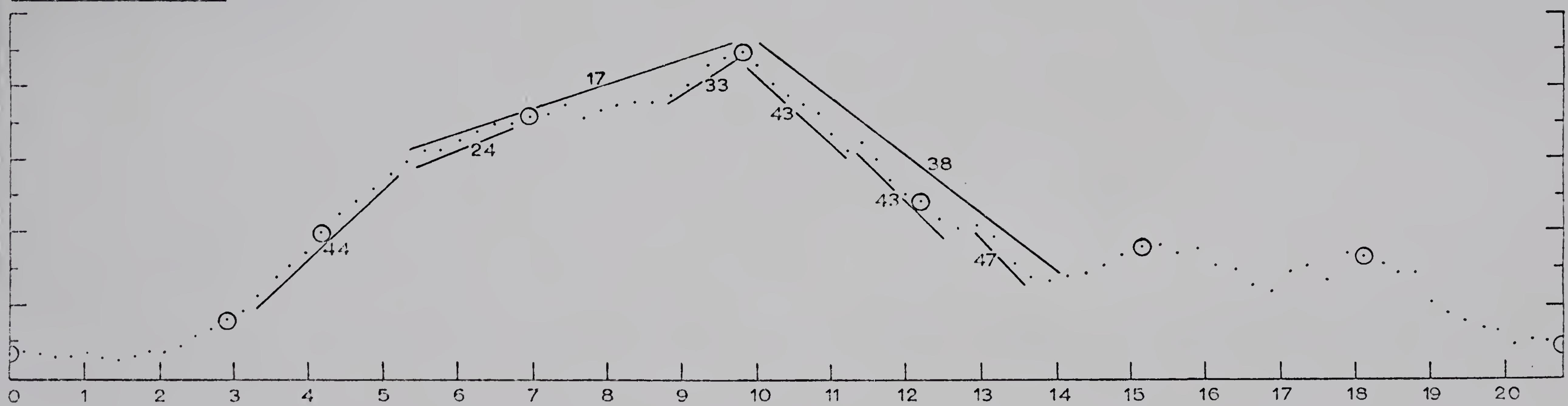

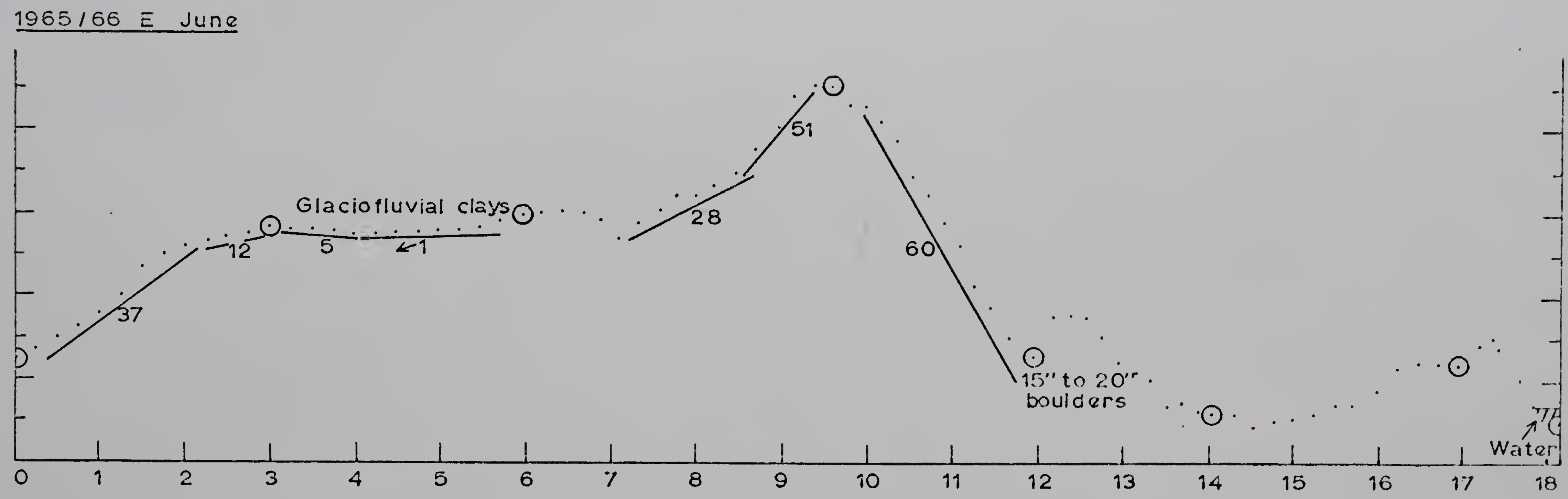
1965/66 E June
Glaciofluvial clays
37
12
5
1
28
51
60
15" to 20" boulders
Water
0
1
2
3
4
5
6
7
8
9
10
11
12
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14
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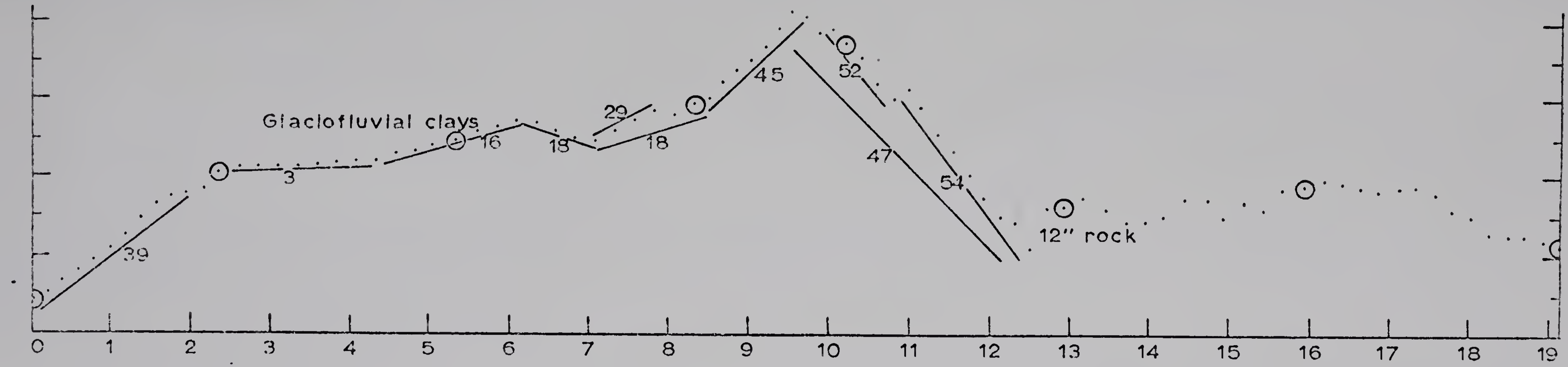
17
18

1965 / 66 E July



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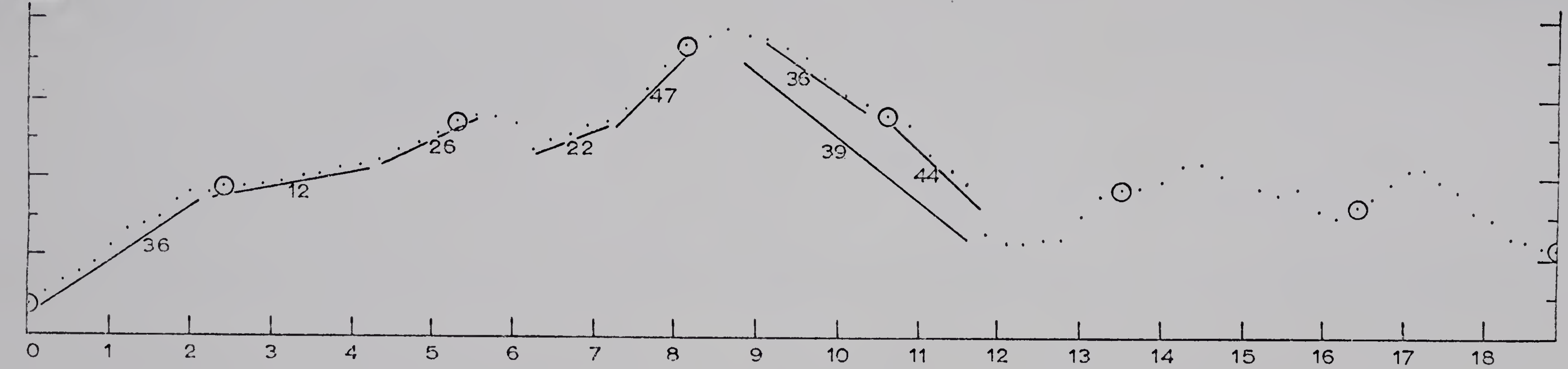

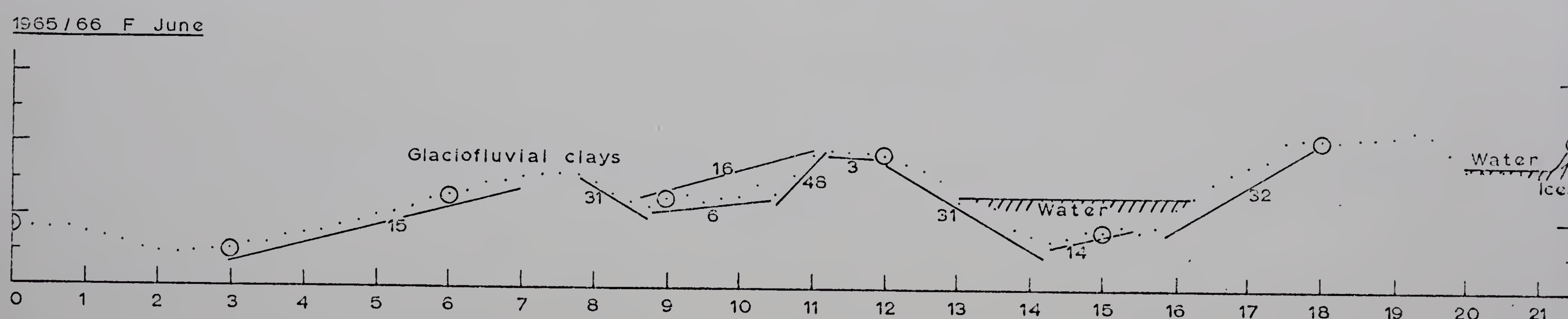

1965/66 F June
Glaciofluvial clays
15
31
16
6
48
3
31
Water
14
32
Water
Ice
0
1
2
3
4
5
6
7
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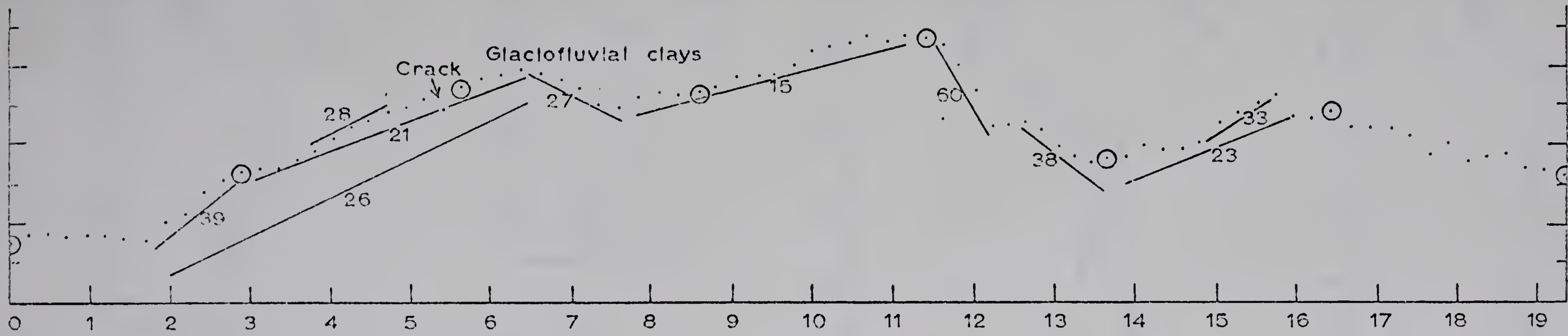
19
20
21

1965 / 66 F July



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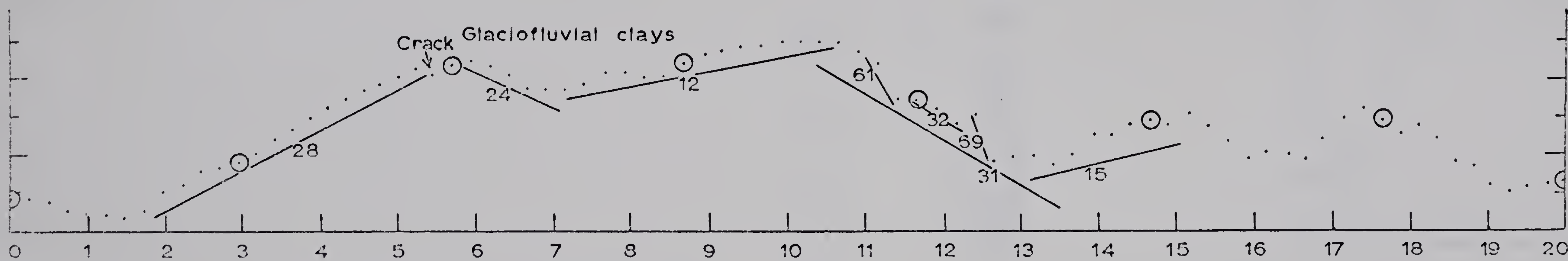
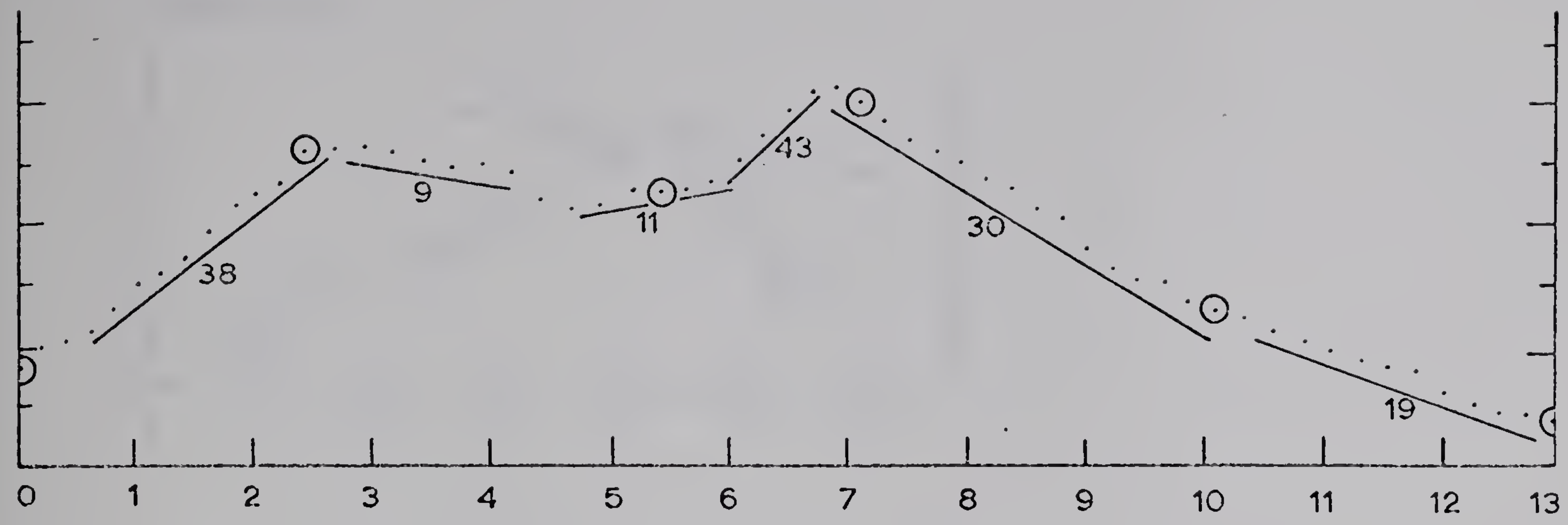
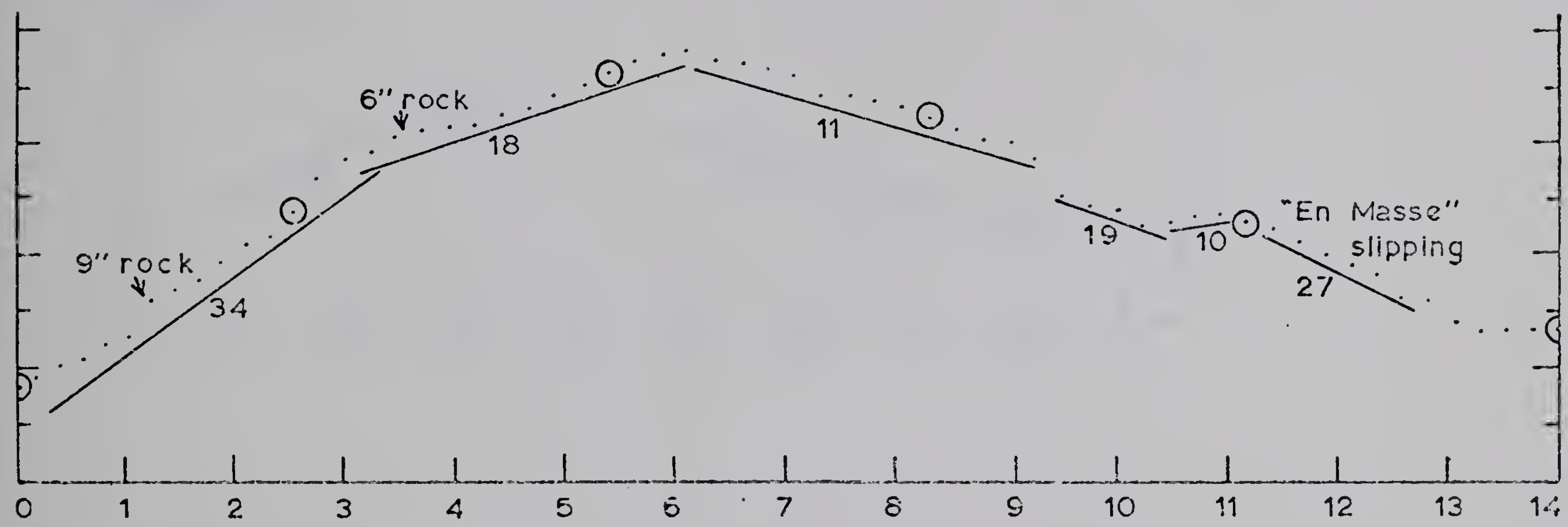


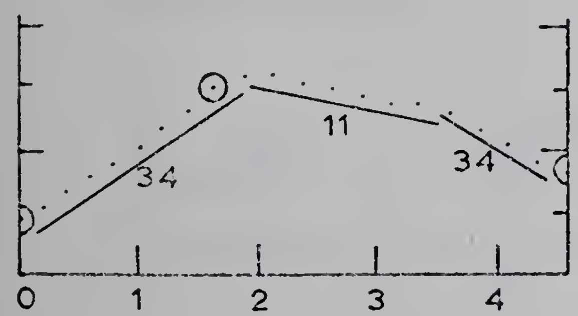
1964 / 65 A



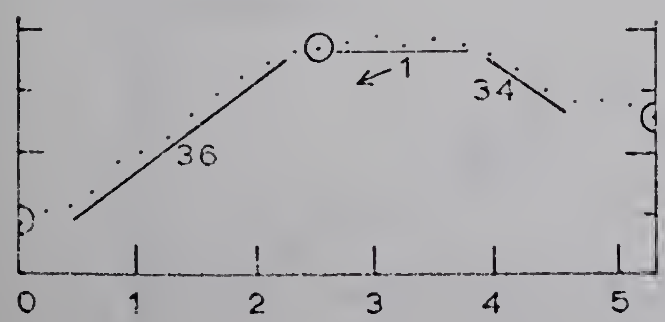
1964 / 65 B



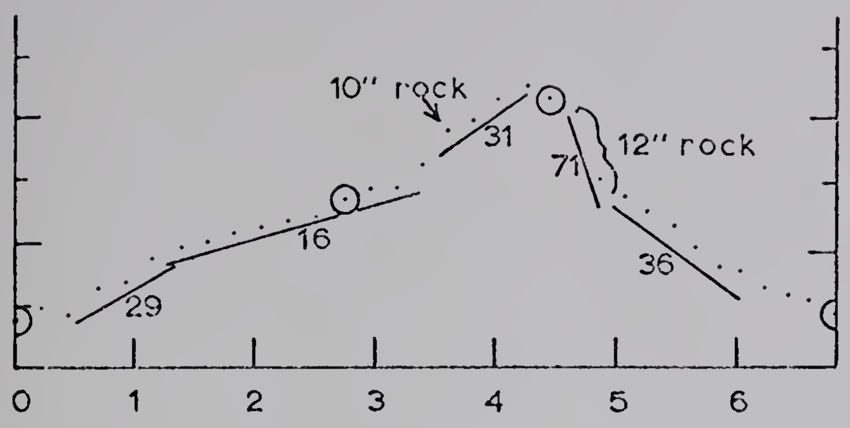
1964 / 65 C



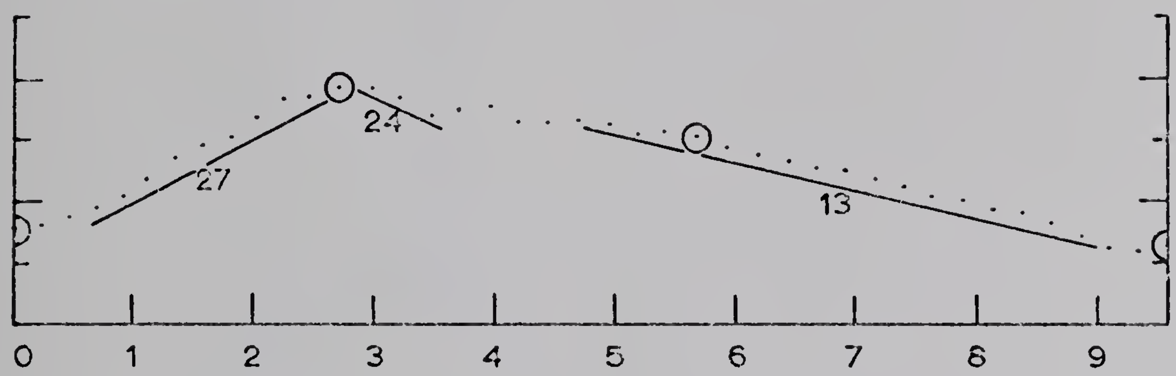
1964 / 65 D



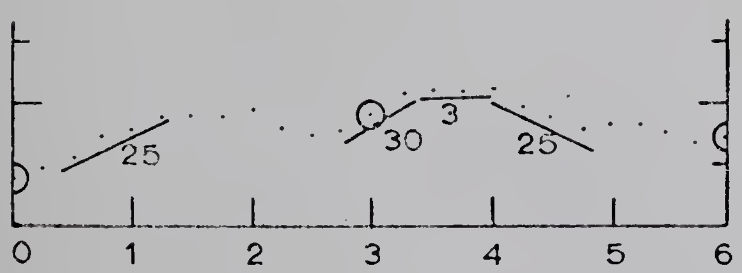
1963 / 64 A



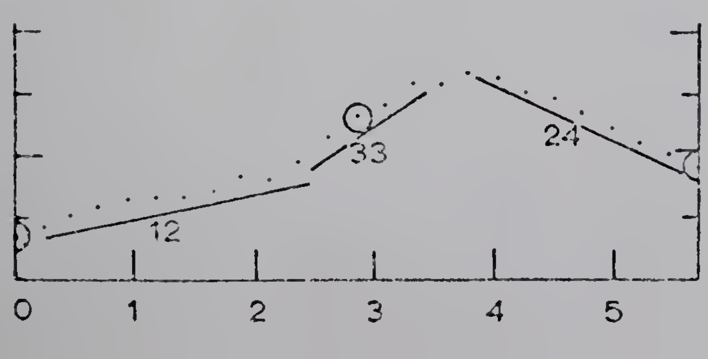
1963 / 64 B



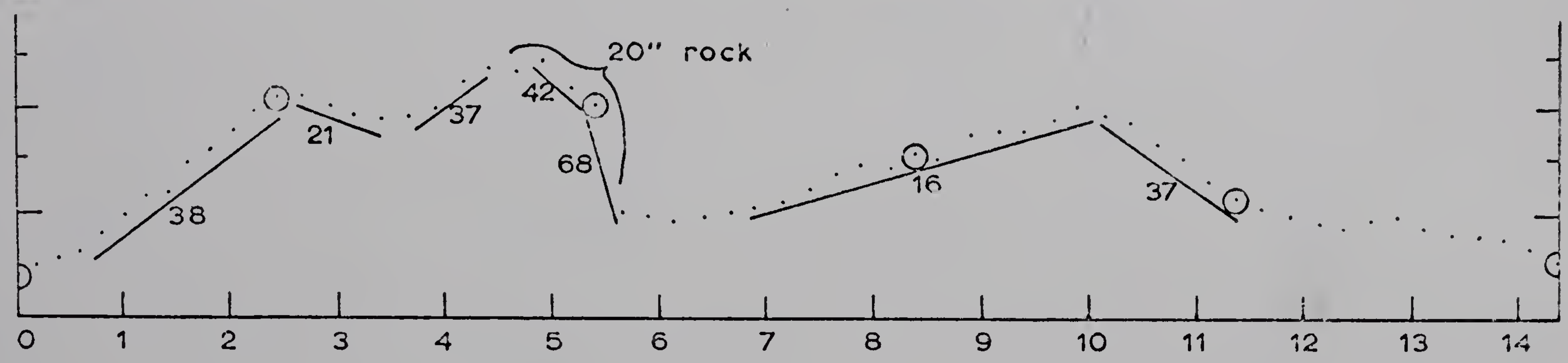
1963 / 64 C



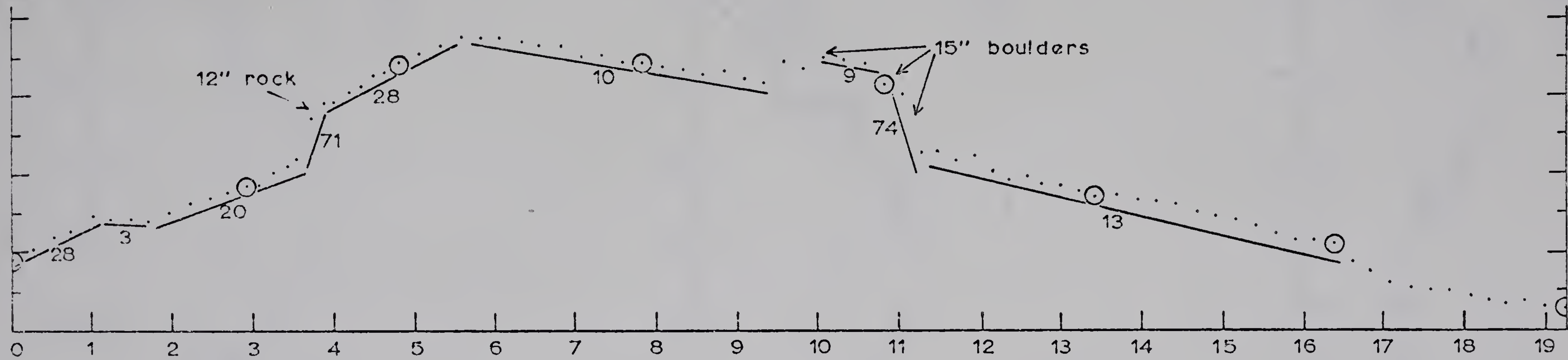
1963 / 64 D



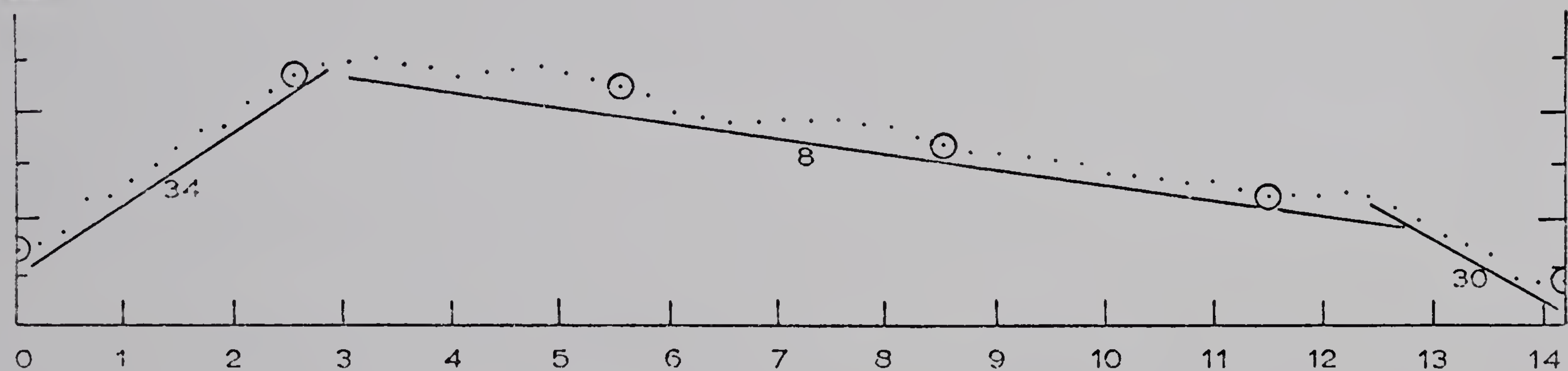
1962 / 63 A



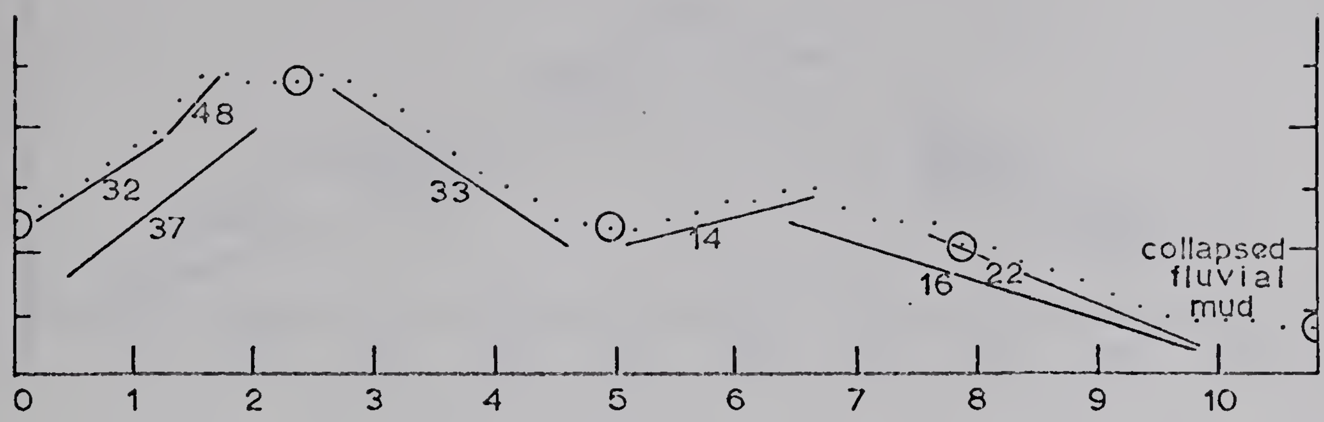
1962 / 63 B



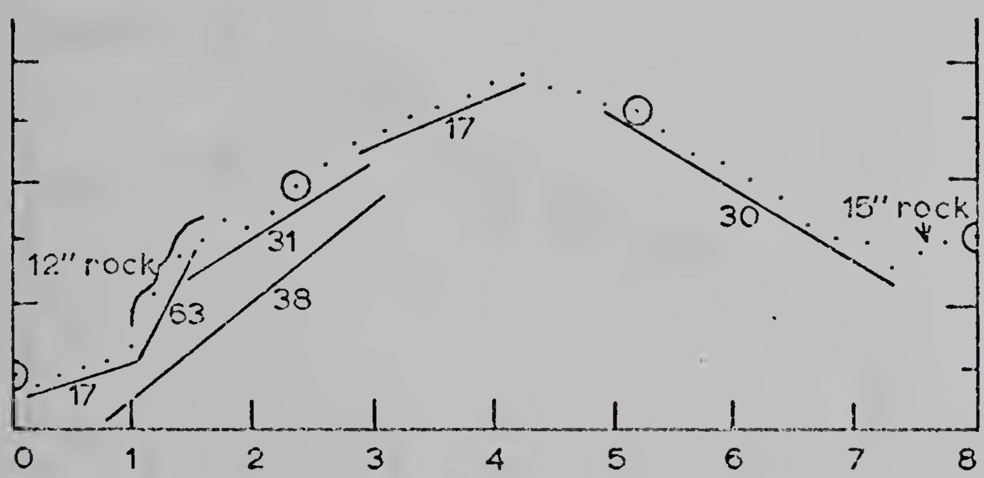
1962 / 63 C



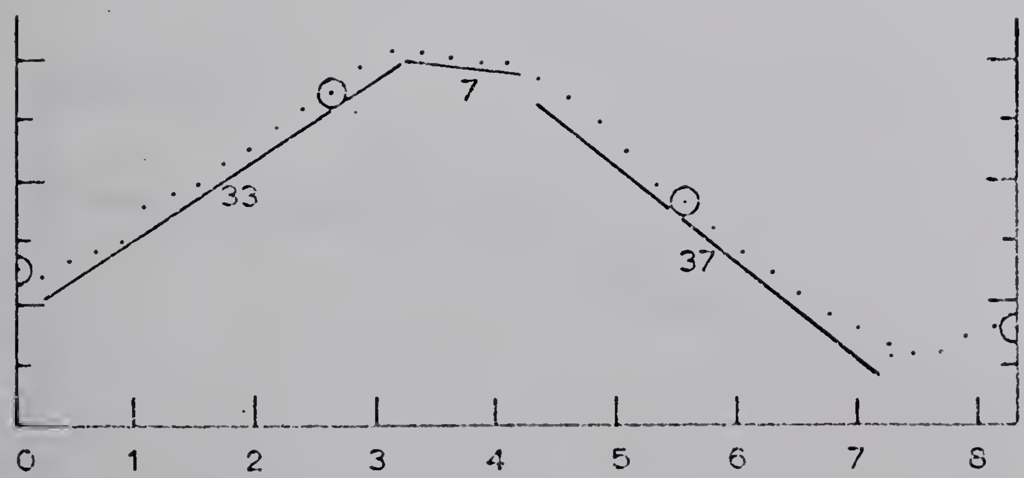
1961 / 62 A



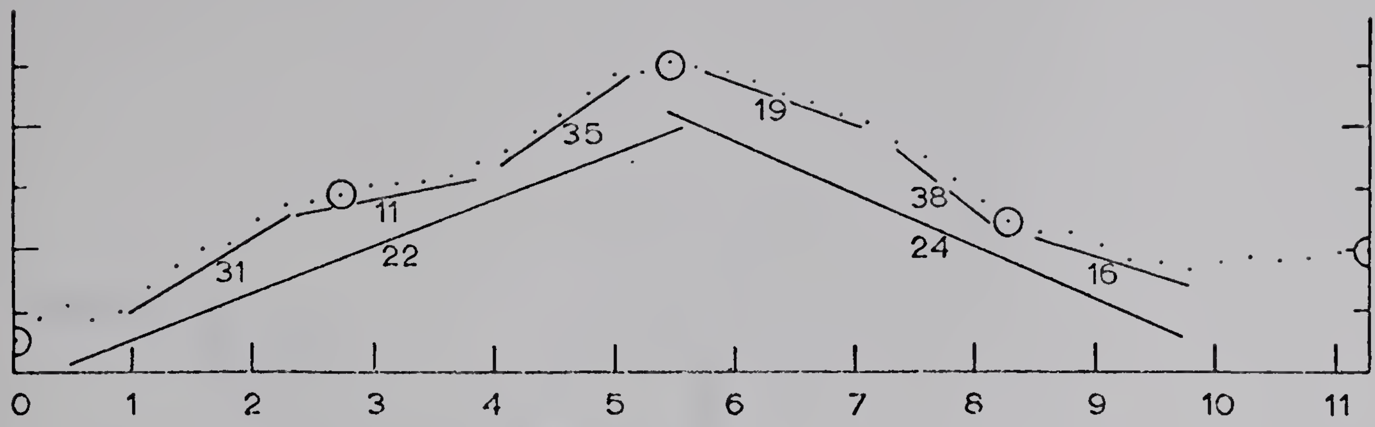
1961 / 62 B



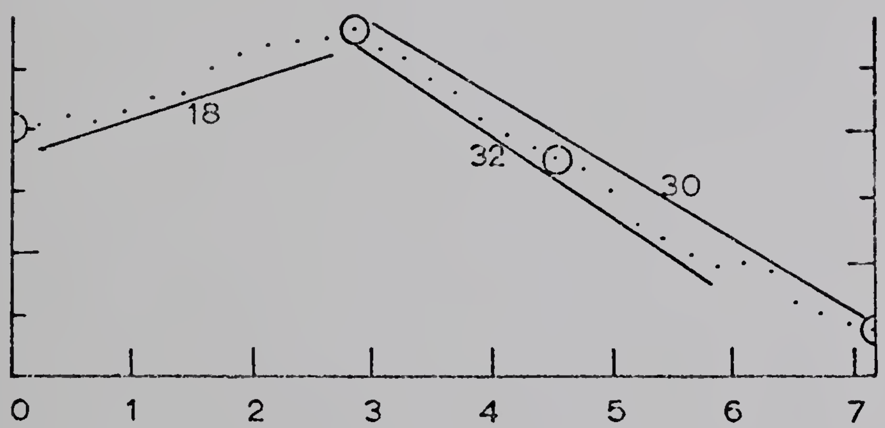
1961 / 62 C



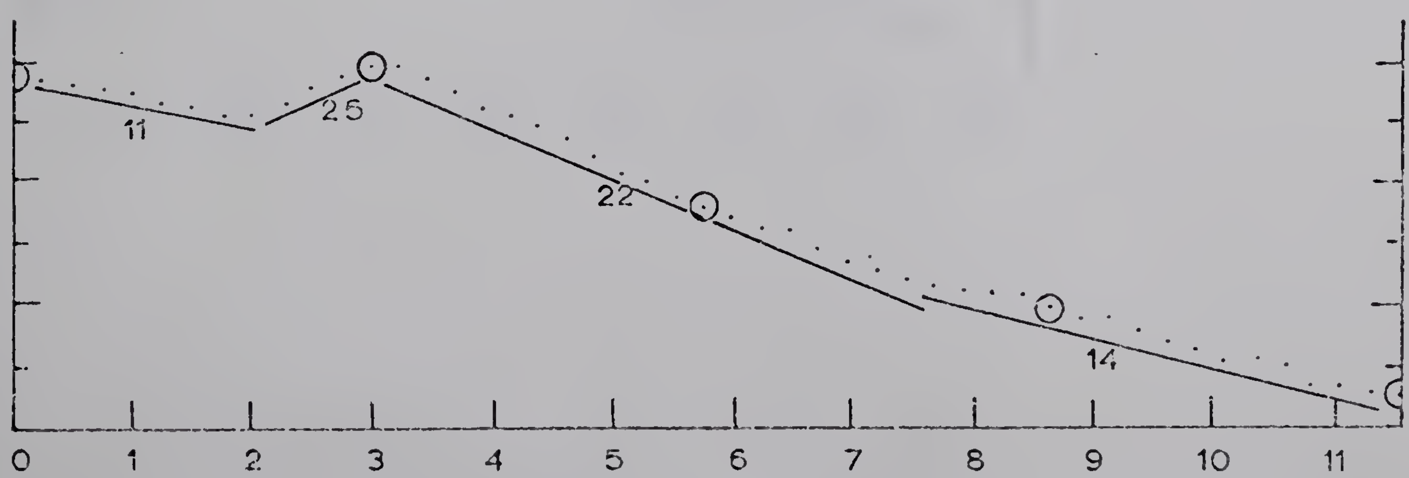
1960 / 61 A



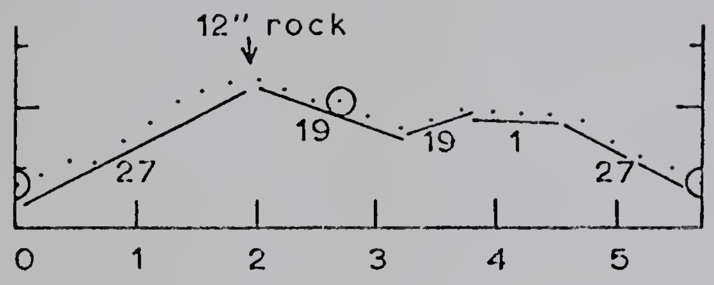
1960 / 61 B



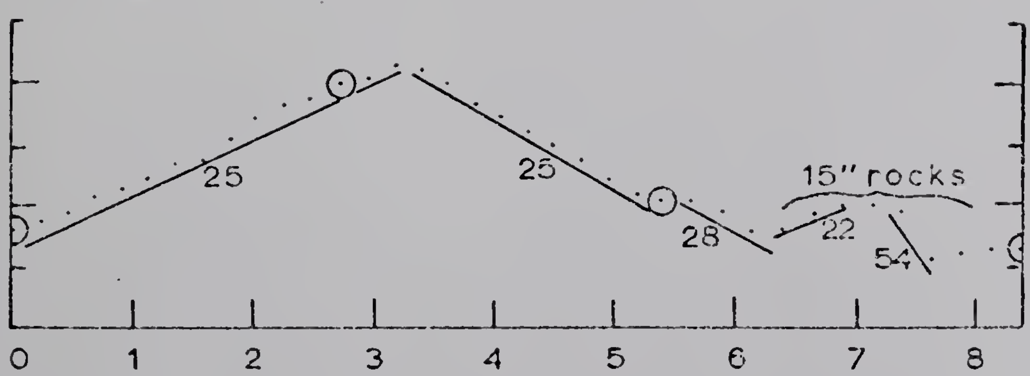
1960 / 61 C



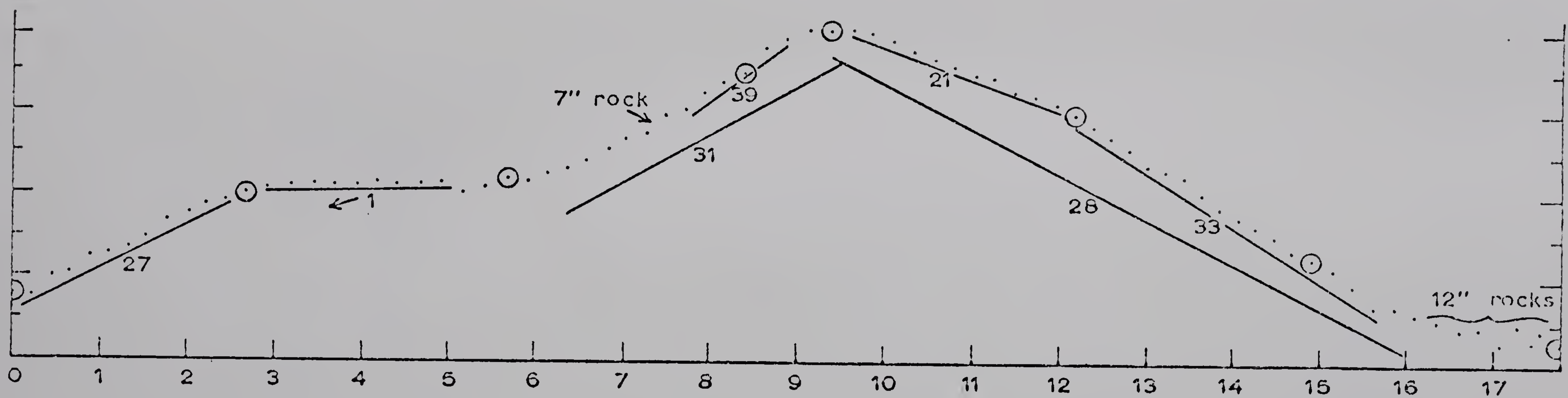
1959 / 60 A



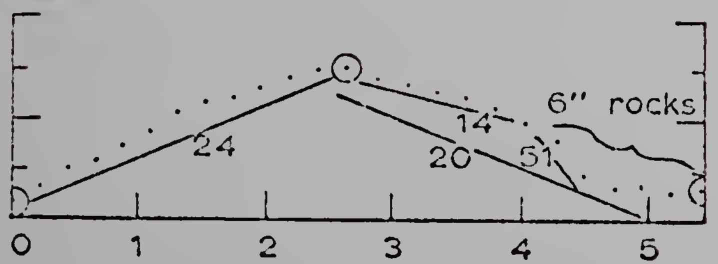
1959 / 60 B

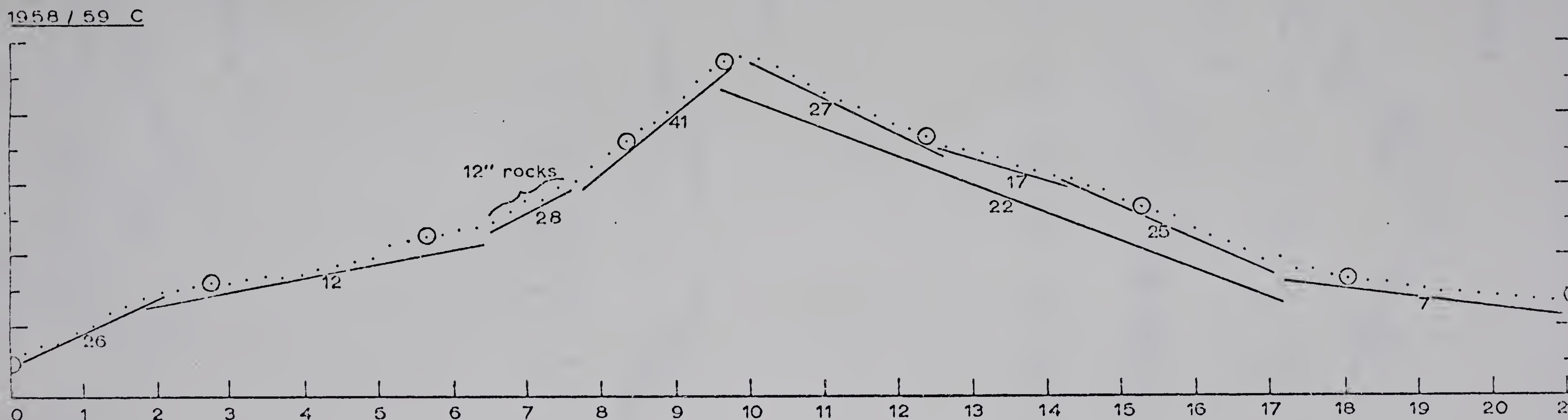


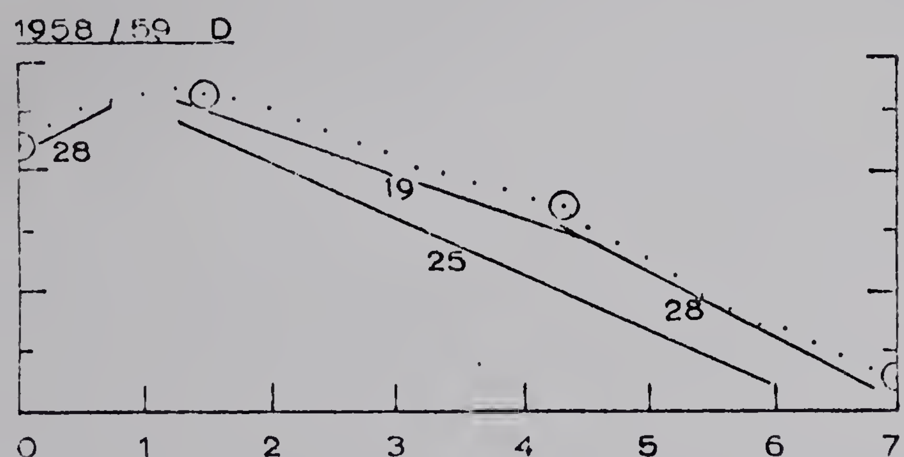
1958 / 59 A



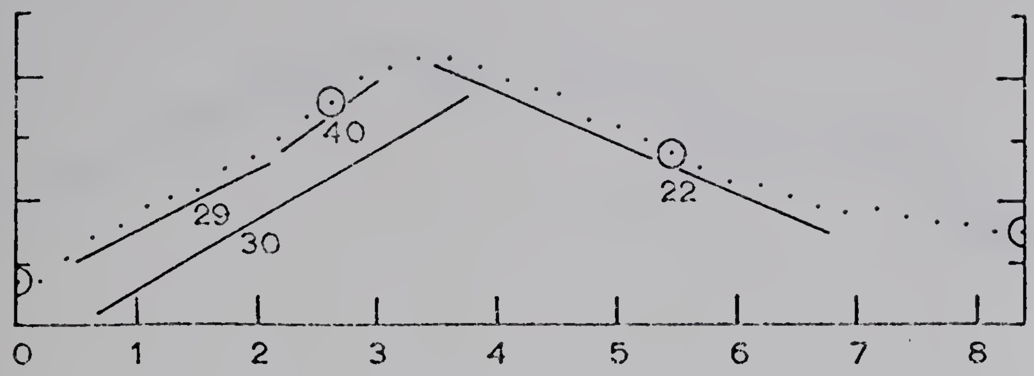
1958 / 59 B



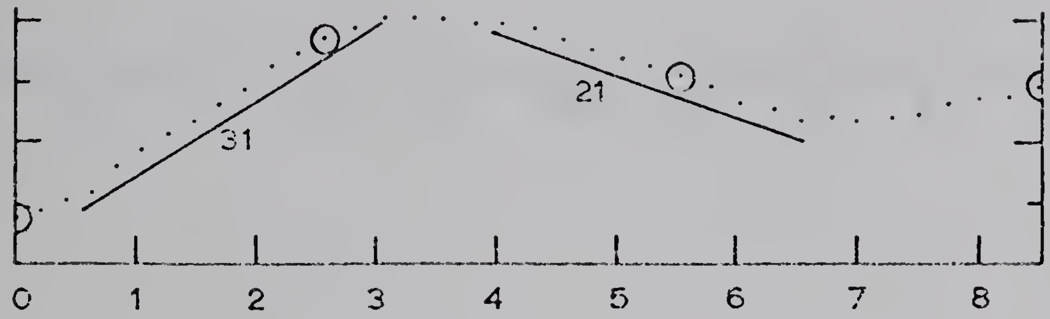

1958 / 59 C
12" rocks
26
12
28
41
27
22
17
25
7
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21


1958 / 59 D
28
19
25
28
0 1 2 3 4 5 6 7

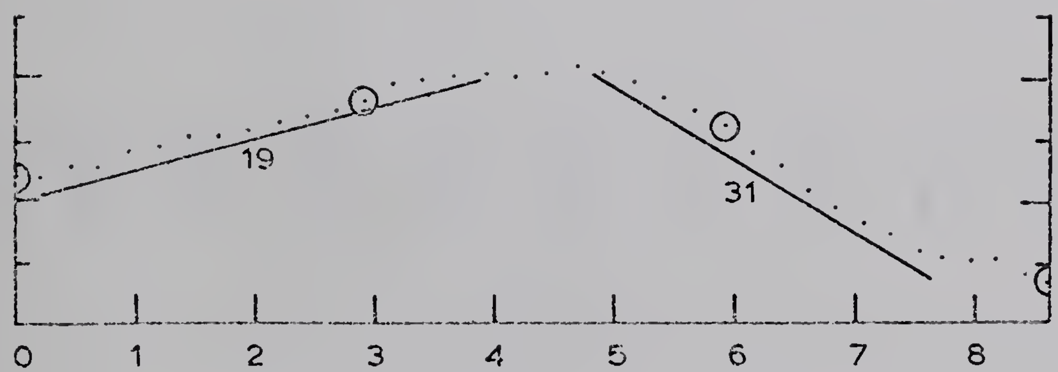
1957 / 58 A



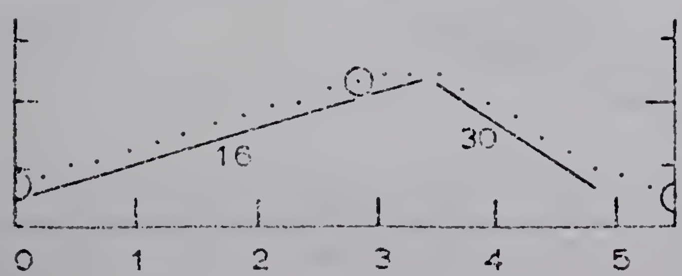
1957 / 58 B



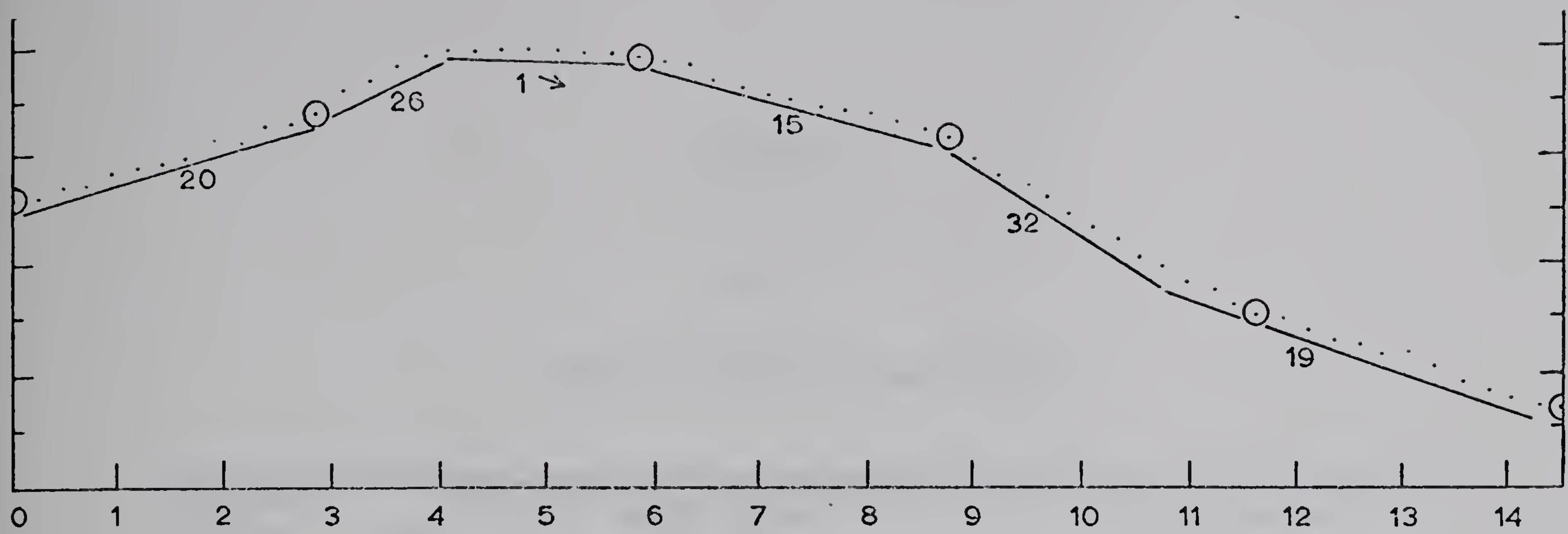
1956 / 57 A



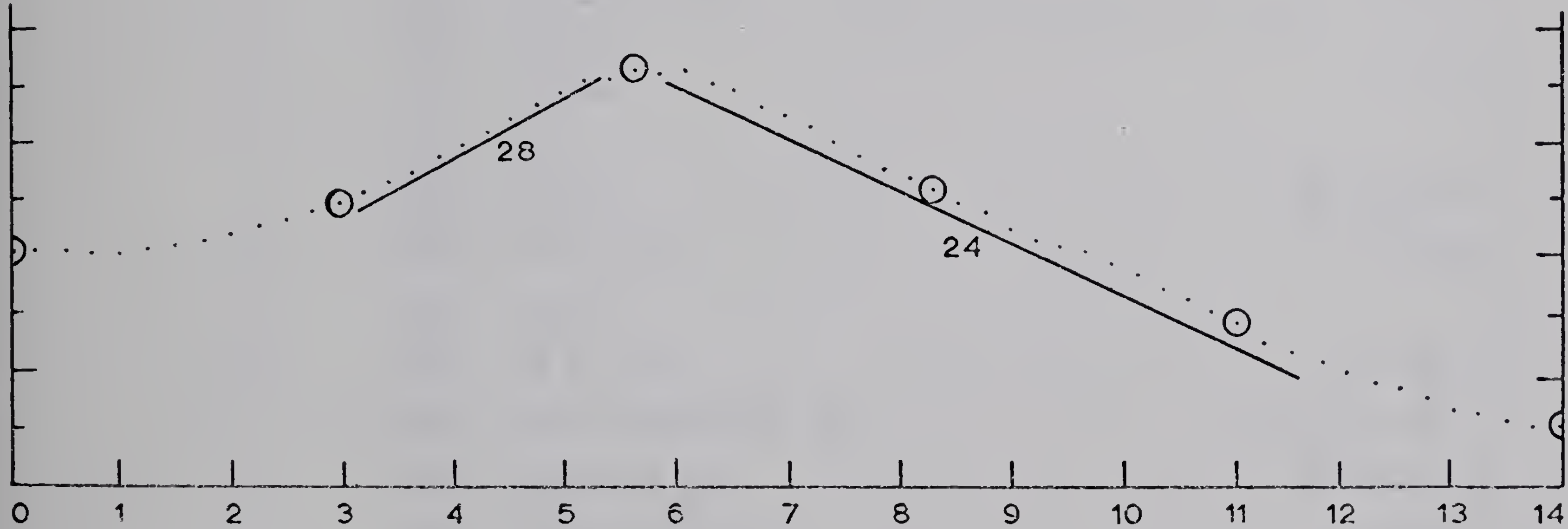
1955 / 56 A



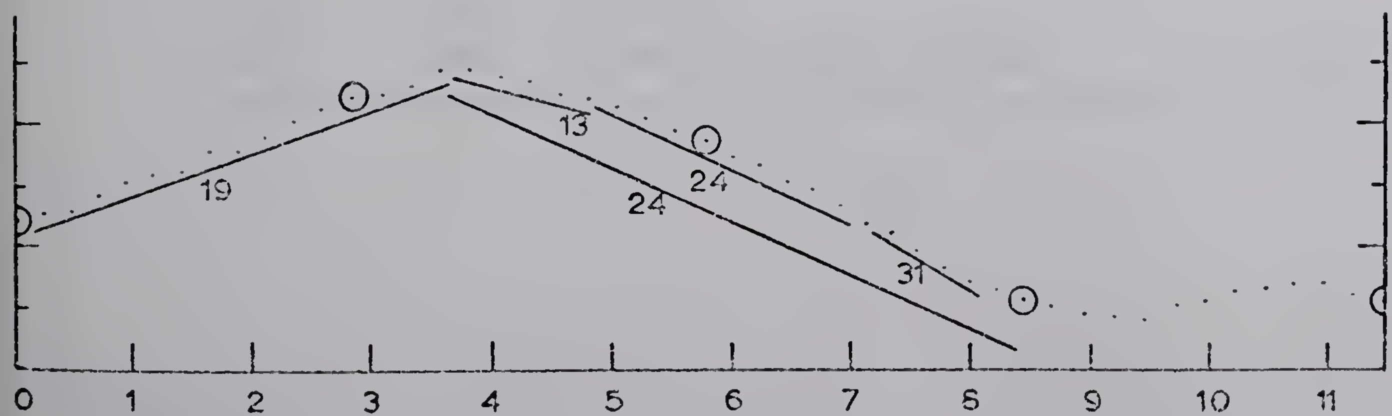
1940



1938



1936



APPENDIX A

Part 2

Brunton Compass Measurements

Brunton Compass Site No.	Date	Back Faces Away from the glacier	Front Faces Towards the glacier
1	1880	27 28	28 28 28
2	1880	26	23
3	1880	20 24 27 28	19 28
4	1890	25 27	28
5	1890	28 28	19 20
6	1890	27	22
7	1890	30 33	20 25 25 25
8	1900	26 34 35	22 26
9	1900	26 30	28
10	1900	28 31 32	27 30 32
11	1908	25 27 28 29 32 28	20 23 25 26 27
12	1908	26 28 28 30	27 28 29 30
13	1908	23 24 29 33 37	25 30 32
14	1908	26 27 28 28	26 27 28 30
15	1900	26 28 31 34	25 29 31
16	1922	25 29	25 28 28 29
17	1919	21 32 33 34 36	23 26 26 28
18	1919	24 26 28 28 30 36	21 23 24 25 27 28 31
19	1925	13 18 19 24 24 28 31 37	21 26 26 29 33
20	1925	28 29 29 31 36	22 24 26 31
21	1935	15 23 26 26	23 31 35 35
22	1935	25 26 36	22 26 28
23	1942	29 29 30 31 32 32 35 35	24 25 25 26 27 31 32

APPENDIX B

Part 1

Slope Measurements for All Moraines

As far as possible the dates of moraines have been spaced to a scale of vertical type space for each year. To avoid crowding, however, the date-rows 1955/56 to 1965/66, and 1935 and 1936 are two spaces apart.

Where a slope facet was measured over a large boulder, this has been marked with an asterisk (*). For example, on the 1958/59 moraine there are four recordings at twenty-eight degrees; one of these corresponds to such a rock face.

Slope Measurements (degrees)

Moraine Dates	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1965/66 June A-H...		1	1	1		2	1	1				1	1		1	4	2	2			1		1		1	2	2	1	2	1	
July A-F...		1		1			1	1	1			1				2	1	3	2		2	2	1	2			2	1	1	1	
Aug. A-F...			1									1	2		2	1	1	3	1	1		1	2		2		1	2	1		2
1964/65............		1								1	1	3							1	2								1			1
1963/64............				1									1	1			1								2	2		1		1	1
1962/63............				1					1	1	1			1			1				1	1							2		1
1961/62............								1							1		1	2					1								1
1960/61............												1	1		1		1		1	1			2		1	1					1
1959/60............		1																		2			*1			2		2	1		
1958/59............		1						1					1		1			1		1	1	1	1		1	2	1	2	*4		
1957/58............																						1	1							1	1
1956/57............																				1											
1955/56............																	1														1
																									1	2	1	1		2	1
1942...............																											1				
1940...............		1														1				1	1				1				1		
1938...............																									2						
1936...............														1						1			1	1	1		2	3	1		
1935...............																1															
1925...............														1					1	1		1	1		3		3		2	3	
1922...............																										2			2	2	
1919...............																						1		1	1		3		3		1
1908...............																					1			2	1	3	4	5	8	3	4
1900...............																							1			1	4	1	3	1	2
1890...............																				1	2		1			4		2	3		1
1880...............																				1	1			1	1		1	2	6		

Moraine Dates	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
1965/66 June A-H...	4	2				2	4	2		2		2	1	1	1			1			1			1						2
July A-F...			1	1			2	1	4		1			2	3		1		1			1		1			1			1
Aug. A-F...	2	1				3		1	2	1		1	1	2		1	2			1						1				
1964/65............				4		1		1					1																	
1963/64............	1		1			1																								
1962/63............				1			2	1				*1																		
1961/62............	*1	2	1				2	1										1												
1960/61............	1	1			1			1																*1						
1959/60............																														
1958/59............	1		1						1		1										*1									
1957/58............	1									1																				
1956/57............	1																													
1955/56............																														
	2	3			2																									
1942...............		1																												
1940...............																														
1938...............	1																													
1936...............	1				2	1																								
1935...............																														
1925...............	3		1			1	1																							
1922...............																														
1919...............		1	1	1		2																								
1908...............		2	1					1																						
1900...............	3	2		2	1																									
1890...............			1																											
1880...............																														

Moraine Dates	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	
1965/66 June A-H...	1	1	1					1						1					1												...June A-H 1965/66
July A-F...																															...July A-F 1965/66
Aug. A-F...	2								1																						...Aug. A-F 1965/66
1964/65............											*1																				............1964/65
1963/64............								*1			*1			*1																	............1963/64
1962/63............			*1																												............1962/63
1961/62............																															............1961/62
1960/61............																															............1960/61
1959/60............																															............1959/60
1958/59............																															............1958/59
1957/58............																															............1957/58
1956/57............																															............1956/57
1955/56............																															............1955/56
1942...............																															1942
1940...............																															1940
1938...............																															1938
1936...............																															1936
1935...............																															1935
1925...............																															1925
1922...............																															1922
1919...............																															1919
1908...............																															1908
1900...............																															1900
1890...............																															1890
1880...............																															1880

APPENDIX B

Part 2

Statistical Data

Moraine Dates	Total Slope Readings	Total Degrees	Range of Slope Values	Five Year Running Means of Ranges
1965/66 June A-H	62	1955	79	-
1965/66 July A-F	47	1347	60	-
1965/66 Aug. A-F	46	1411	68(79[1])	- (64[1])
1964/65	18	408	43	54
1963/64	15	399	69	56
1962/63	19	586	72	53
1961/62	16	474	58	42
1960/61	15	349	28	33
1959/60	10	247	54	30
1958/59	24	594	51	22
1957/58	6	173	20	18
1956/57	2	50	13	15
1955/56	2	46	15	16
1942	15	443	12	18
1940	6	113	32	21
1938	2	52	5	15
1936	5	111	19	17
1935	14	382	22	17
1925	22	586	25	16
1922	6	164	5	14
1919	15	431	16	15
1908	35	969	18	-
1900	21	611	14	-
1890	15	382	15	-
1880	13	334	10	-

1 Bracketed figures are averaged from all 1965/66 data.

Statistical Data (continued)

Moraine Dates	Central Values	Five Year Running Means of Central Values	Upper Limits	Five Year Running Means of Upper Limits
1965/66 June A-H	40	-	79	-
1965/66 July A-F	31	-	60	-
1965/65 Aug. A-F	36(40)	-(34)	69(79[2])	-(66[2])
1964/65	22	31	42	58
1963/65	36	32	71	60
1962/63	38	30	74	56
1961/62	35	28	63	49
1960/61	24	26	38	43
1959/60	27	26	54	41
1958/59	26	26	51	37
1957/58	30	24	40	34
1956/57	25	24	31	31
1955/56	22	23	30	31
1942	29	24	35	32
1940	16	23	32	33
1938	26	25	28	32
1936	22	25	31	34
1935	25	26	36	35
1925	25	27	37	35
1922	27	27	29	34
1919	27	27	36	34
1908	28	-	37	-
1900	28	-	35	-
1890	26	-	33	-
1880	24	-	28	-

2 Bracketed figures are averaged from all 1965/66 data.

Statistical Data (continued)

Moraine Dates	Chi-Squared Values	Degrees of Freedom[3]	Probability Values[4]
1965/66 June A-H	125	61	< 0.01
1965/66 July A-F	71	46	0.01-0.02
1965/66 Aug. A-F	64	45	0.02-0.05
1964/65	22	17	0.2-0.3
1963/64	30	14	0.01-0.02
1962/63	22	18	0.2-0.3
1961/62	38	15	0.01-0.001
1960/61	28	14	0.02-0.05
1959/60	42	9	< 0.01
1958/59	60	23	< 0.01
1957/58	14	5	0.02-0.05
1956/57	2	1	0.3-0.5
1955/56	2	1	0.3-0.5
1942	84	14	< 0.01
1940	8	5	0.2-0.3
1938	2	1	0.3-0.5
1936	12	4	0.02-0.05
1935	46	13	< 0.01
1925	86	21	< 0.01
1922	30	5	< 0.01
1919	68	14	< 0.01
1908	262	34	< 0.01
1900	154	20	< 0.01
1890	102	14	< 0.01
1880	112	12	< 0.01

3 Degrees of Freedom equal (N - 1), where N is the total number of slope readings.

4 Fisher, R.Y. and Yates, F., Statistical Tables for Biological, Agricultural and Medical Research, Hafner Publishing Co., New York, 1963 (6th edition), p. 47.

Statistical Data (continued)

Moraine Dates	Mean Slopes[5]	Five Year Running Averages of Means	Median Slope Values	Five Year Running Means of Medians
1965/66 June A-H	31.53	-	31	-
1965/66 July A-F	28.66	-	27	-
1965/66 Aug. A-F	30.67(30.41)[6]	(28.03)[6]	30(29)[6]	(27)[6]
1964/65	22.67	26.60	23	26
1963/64	26.60	27.01	25	26
1962/63	30.84	26.64	28	26
1961/62	29.63	26.24	32	27
1960/61	23.27	25.31	22	25
1959/60	24.70	25.26	25	25
1958/59	24.75	26.20	25	26
1957/58	28.83	25.04	29	25
1956/57	25.00	24.47	25	25
1955/56	23.00	23.91	23	25
1942	29.53	24.77	30	25
1940	18.83	24.19	20	25
1938	26.00	25.89	26	26
1936	22.20	26.44	24	27
1935	27.29	27.54	27	27
1925	26.64	27.68	27	28
1922	27.33	27.44	28	27
1919	28.73	27.12	27	27
1908	27.69	-	28	-
1900	28.00	-	29	-
1890	25.47	-	25	-
1880	25.69	-	27	-

5 These are arithmetic averages only and do not represent the accuracy of measurements in the field.

6 Bracketed figures are averaged from all 1966 data.

Statistical Data (continued)

Moraine Dates	Modes[7]	Five Year Running Means of Modes	Generalized Range	Five Year Running Means of Generalized Range
1965/66 June A-H	40	-	79	-
1965/66 July A-F	20	-	60	-
1965/66 Aug. A-F	40(40)[8]	-(36)[8]	68(79)[8]	-(47)[8]
1964/65	35	33	43	37
1963/64	30	32	34	34
1962/63	40	32	36	35
1961/62	35	30	42	32
1960/61	25	30	28	26
1959/60	30	29	28	23
1958/59	30	28	41	20
1957/58	30	28	20	18
1956/57	-[9]	-[9]	13	15
1955/56	-[9]	-[9]	15	16
1942	35	28	12	18
1940	20	27	32	21
1938	-[9]	-[9]	5	15
1936	25	29	19	17
1935	30	30	22	17
1925	30	30	25	16
1922	30	30	5	14
1919	30	30	16	15
1908	30	-	18	-
1900	30	-	14	-
1890	30	-	15	-
1880	30	-	10	-

7 Modes are in five degree classes (40 = class 35^{o} to 40^{o}).
8 Bracketed figures are averaged from all 1966 values.
9 No valid mode available since these moraines have only two slope recordings.

Statistical Data (continued)

Moraine Dates	Generalized Central Values	Generalized Upper Limits	Generalized Medians	Five Year Running Means of Generalized Medians
1965/66 June A-H	40	-	-	-
1965/66 July A-F	31	-	-	-
1965/66 Aug. A-F	36 (40)[10]	- (79)[10]	- (29)[10]	- (26)[10]
1964/65	22	42	23	25
1963/64	20	36	25	25
1962/63	21	38	21	25
1961/62	27	48	32	27
1960/61	25	38	22	25
1959/60	15	28	25	25
1958/59	21	41	25	26
1957/58	30	40	29	25
1956/57	25	31	25	25
1955/56	23	30	23	25
1942	29	35	30	25
1940	16	32	20	25
1938	26	28	26	26
1936	22	31	24	27
1935	25	36	27	27
1925	25	37	27	28
1922	27	29	28	27
1919	27	36	27	27
1908	28	37	28	-
1900	28	35	29	-
1890	26	33	25	-
1880	24	28	27	-

10 Bracketed figures are averaged from all 1966 values.

APPENDIX C

Slope Values on the Main Faces of the Moraines of the Athabaska Glacier[1]

Faces away from the glacier					
Moraine Dates	Slope Recordings	Aggregate	No.	Average[2]	Five Year Running Means of Averages
1965/66 June A-H	23 29 37 37 38 43 48 51 60 62	428	10	42.8	34.3
1965/66 July A-F	15 17 20 34 37 39 45 45	252	8	31.5	31.9
1965/66 Aug. A-F	12 17 22 30 36 43 44 47	250	8	31.2	32.8
1964/65	34 36 36 38	142	4	37.3	30.9
1963/64	25 27 29 30 33	144	5	28.8	28.6
1962/63	16 28 34 27 38	153	5	30.6	28.8
1961/62	33 37 38	108	3	36.0	28.8
1960/61	18 22 25	65	3	21.7	25.4
1959/60	25 27	52	2	26.6	24.2
1958/59	24 26 27 28 31 41	177	6	29.6	24.2
1957/58	30 31	61	2	30.5	23.9
1956/57	19	19	1	19.0	21.6
1955/56	16	16	1	16.0	-
1940	26	26	1	26.0	-
1938	28	28	1	28.0	-
1936	19	19	1	19.0	-

1 Only those moraines surveyed by Abney level have been considered. Large boulders have little effect in distorting slope measurements on the larger moraines.

2 These are arithmetic averages only and do not represent the accuracy of measurements in the field.

Slope Values on the Main Faces of the Moraines of the

Athabaska Glacier (continued)[3]

Moraine Dates	Faces towards the glacier: Slope Recordings	Aggregate	No.	Average[4]	Five Year Running Means of Averages
1965/66 June A-H	15 22 31 40 42 60 79	289	7	41.3	32.9
1965/66 July A-F	17 39 39 47 60	202	5	40.4	29.9
1965/66 Aug. A-F	11 14 31 36 38 39	169	6	28.2	28.5
1964/65	11 30 34 34	109	4	27.2	27.9
1963/64	24 24 25 36	109	4	27.2	27.7
1962/63	13 30 37	80	3	26.7	27.0
1961/62	30 33 37	100	3	33.3	26.0
1960/61	22 24 30	76	3	25.3	25.5
1959/50	25 27	52	2	26.0	26.4
1958/59	20 22 25 28	95	4	23.7	27.6
1957/58	21 22	43	2	21.5	27.7
1956/57	31	31	1	31.0	-
1955/56	30	30	1	30.0	-
1940	32	32	1	32.0	-
1938	24	24	1	24.0	-
1936	24	24	1	24.0	-

3 Only those moraines surveyed by Abney level have been considered. Large boulders have little effect in distorting slope measurements on the larger moraines.

4 These are arithmetic averages only and do not represent the accuracy of measurements in the field.

APPENDIX D

Surface Roughness Data

Moraine Date and Section	Individual Section Lines: Angle (Θ) (degrees)	Cumulative Length (L) (feet)	Roughness $\frac{\theta}{L}$
1965/66 June G	850	11.25	75.55
H	800	15.25	52.46
A	1720	20.25	84.94
B	1320	18.50	71.35
C	1460	19.50	74.87
D	2170	27	80.37
E	1870	28	66.79
F	1680	26	64.62
1965/66 July A	790	13	60.77
B	1180	17.25	68.41
C	1170	18.75	62.40
D	2120	27.75	76.40
E	2230	27.25	81.84
F	2250	27	83.33
1965/66 Aug. A	1310	18.75	69.87
B	1710	21	81.43
C	2980	19.75	150.87
D	3000	28.75	104.35
E	1730	27	64.07
F	2140	27.75	77.12
1964/65 A	1090	18	60.55
B	1110	19	58.42
C	260	6	43.33
D	370	7.25	51.03
1963/64 A	740	10.50	70.48
B	670	12.50	53.60
C	480	7.50	64.00
D	430	7.25	59.31
1965/66 June G + H	1650	26.50	62.26
1965/66 June A to F	10220	139.25	73.39

Surface Roughness Data (continued)

Moraine Date and Section		Individual Section Lines: Angle (θ) (degrees)	Cumulative Length (L) (feet)	Roughness $\frac{\theta}{L}$
1962/63	A	1150	20.25	56.79
	B	2430	26.75	90.84
	C	860	18.75	45.87
1961/62	A	660	15.75	41.90
	B	770	11.50	66.96
	C	640	12.25	52.24
1960/61	A	670	15.25	43.93
	B	560	9.75	57.43
	C	560	14.75	37.97
1959/60	A	400	7.25	55.17
	B	630	11.50	54.78
1958/59	A	1400	24	58.33
	B	370	7.50	49.33
	C	1080	27.50	39.27
	D	330	9	36.67
1957/58	A	490	11.25	43.56
	B	360	11.25	32.00
1956/57		410	11.50	35.65
1955/56		180	6.75	26.67
1940		690	18.50	37.30
1938		550	18	30.56
1936		570	15	38.00

Surface Roughness Data (continued)

Moraine Date and Sections	Each Year's Section Lines Integrated: Cumulative Angle (θ) (degrees)	Cumulative Length(L) (feet)	Roughness	Five Year Running Means of Roughness
1965/66 June A-H	11870	165.75	71.60	70.75
1965/66 July A-F	9740	131	74.35	69.94
1965/66 Aug. A-F	12870	143	90.00	65.55
1964/65	2830	50.25	56.32	56.56
1963/64	2320	37.75	61.49	56.28
1962/63	4440	65.75	67.53	53.33
1961/62	2070	39.50	52.41	47.38
1960/61	1790	39.75	45.03	44.03
1959/60	1030	18.75	54.93	40.36
1958/59	3180	68	46.76	36.83
1957/58	850	22.50	37.78	33.59
1956/57	410	11.50	35.65	33.64
1955/56	180	6.75	26.67	-
1940	690	18.50	37.30	-
1938	550	18	30.56	-
1936	570	15	38.00	-

APPENDIX E

Part 1: Clay Fraction Calculations

Sample Date	Total Weight Gross Pan Net	Total Weight held by 230 Mesh Sieve Gross Pan Net	Wt.<230 =Total-Wt.>230	%<230
1965/66 X	625.5-229.5=396.0	430.3-152.5=277.8	118.2	29.85
1964/65 X	452.8-158.4=294.4	341.2-152.7=188.5	105.9	35.97
1964/65Z	776.9-229.4=547.5	568.0-152.5=415.5	132.0	24.11
1962/63Z	560.2-176.3=283.9	337.3-151.9=185.4	98.5	34.70
1955 Z	627.7-196.4=431.3	440.2-152.3=287.9	143.4	33.24
1966 Summer	749.7-229.5=520.2	561.0-152.5=408.5	111.7	21.47
1965/66	554.4-196.4=358.2	381.7-152.1=229.6	128.6	28.52
1965 Summer	621.5-175.3=445.2	482.1-151.8=330.3	114.9	25.81
1963/64	623.0-229.5=393.5	397.6-151.8=245.8	147.7	37.53
1963 Summer	679.6-229.4=450.2	500.1-152.5=347.6	102.6	22.78
1962/63	563.3-229.5=333.8	361.4-152.5=208.9	124.9	37.41
1961/62	522.7-196.3=326.4	366.2-152.5=213.7	112.7	34.52
1961 Summer	699.6-229.4=470.2	489.7-152.7=337.0	133.2	28.32
1960/61	497.2-229.4=267.8	311.8-152.3=159.5	108.3	40.44
1960 Summer	537.8-208.1=329.7	426.9-152.1=274.8	54.9	16.65
1959/60	485.1-196.3=288.8	336.4-151.8=184.6	104.2	36.08
1959 Summer	632.6-229.5=403.1	504.5-152.5=352.0	51.1	12.67
1958/59	558.8-196.4=362.4	486.2-151.8=334.4	28.0	7.72
1958 Summer	642.0-229.5=412.5	472.1-151.8=320.3	92.2	22.35
1957 Summer	591.6-176.3=415.3	414.1-151.9=262.2	153.1	36.86
1956/57	446.0-176.3=269.7	347.3-152.6=194.7	75.0	27.80
1956 Summer	860.0-229.4=630.6	568.3-152.6=415.7	214.9	34.07
1955/56	557.9-229.4=328.5	363.0-152.5=210.5	118.0	35.92
1955 Summer	633.7-229.5=404.2	468.5-152.7=315.8	88.4	21.87
1940	618.2-176.3=441.9	389.5-152.5=237.0	204.9	46.36
1938	478.5-176.3=302.2	337.3-152.5=184.8	117.4	38.84
1936	611.9-229.5=382.4	366.5-151.9=214.6	167.8	43.88
1925	643.0-219.2=423.9	441.4-152.6=288.8	135.0	31.85
1908	648.2-176.3=471.9	563.8-152.3=411.4	60.4	12.79
1900	595.3-196.3=399.0	431.9-152.7=279.2	119.8	30.02
1890	734.5-229.4=505.1	623.8-152.5=471.3	33.8	6.69
1880	553.1-196.4=356.7	433.9-152.5=281.4	75.3	21.11

Certain samples were dry-sieved and have not been listed. These are 1965/66 Y and Z, 1964/65 W and Y, 1962 Summer, 1957/58, 1942, 1935, 1922 and 1919, 1964/65 and 1964 Summer.

Clay Fraction Calculations (continued)

Sample Date	Clay Fraction Percentage	Five Year Running Means of Recent Winter and all Other Samples	Five Year Running Means of Summer Samples
1966 Summer	21.47		23.00
1965/66	28.52	35.68	
1965 Summer	25.81		21.24
1963/64	37.53	37.19	
1963 Summer	22.78		20.55
1962/63	37.41	31.23	
1961/62	34.52	29.31	
1961 Summer	28.32		23.37
1960/61	40.44	29.59	
1960 Summer	16.65		24.52
1959/60	36.08	30.77	
1959 Summer	12.67		25.56
1958/59	7.72	31.32	
1958 Summer	22.35		-
1957 Summer	36.86		-
1956/57	27.80	38.56	
1956 Summer	34.07		-
1955/56	35.92	39.37	
1955 Summer	21.87		-
1940	46.36	34.74	
1938	38.84	31.47	
1936	43.88	25.04	
1925	31.85	20.49	
1908	12.79	-	
1900	30.02	-	
1890	6.69	-	
1880	21.11	-	

Part 2: Stone Sphericity

Sample Date	No. of Stones	Aggregate Sphericity	Average Sphericity
1966 Summer	41	222	5.4
1965/66	38	199	5.2
1965 Summer	33	176	5.3
1964/65	45	229	5.1
1964 Summer	34	196	5.8
1963/64	34	187	5.5
1963 Summer	48	225	4.7
1962/63	23	116	5.0
1962 Summer	41	220	5.4
1961/62	25	119	4.8
1961 Summer	55	283	5.1
1960/61	20	102	5.1
1960 Summer	55	290	5.3
1959/60	22	115	5.2
1959 Summer	61	276	4.5
1958/59	46	238	5.2
1958 Summer	36	168	4.7
1957/58	40	199	5.0
1957 Summer	29	140	4.8
1956/57	39	216	5.5
1956 Summer	52	281	5.4
1955/56	28	151	5.4
1955 Summer	58	317	5.5
Average sphericity, 1955 Summer to 1966 Summer...............			5.2
1942	40	229	5.7
1940	21	108	5.1
1938	31	172	5.5
1936	23	120	5.2
1935	40	232	5.8
1925	22	124	5.6
1919	55	300	5.5
1908	49	259	5.3
1900	33	189	5.7
1890	73	359	4.9
1880	46	239	5.2
Average sphericity, 1880 to 1942............................			5.4
1965/66 X	44	242	5.5
1965/66 Y	14	72	5.1
1965/66 Z	39	222	5.7
1964/65 W	25	122	4.9
1964/65 X	30	138	4.6
1964/65 Y	14	78	5.6
1964/65 Z	32	160	5.0
1962/63 Z	38	216	5.7
1955 Summer Z	20	109	5.5

No sample collected for the 1922 moraine. The till of this moraine has great variations: no one place is representative.

Part 3: Stone Roundness

Sample Date	No. of Stones	Aggregate Roundness	Average Roundness	Five Year Running Means of Roundness
1966 Summer	47	187	4.0	4.3
1965/66	38	159	4.2	4.5
1965 Summer	33	150	4.5	4.5
1964/65	45	200	4.4	4.6
1964 Summer	34	150	4.4	4.6
1963/64	34	174	5.1	4.6
1963 Summer	48	208	4.3	4.4
1962/63	23	112	4.9	4.5
1962 Summer	41	169	4.1	4.5
1961/62	25	109	4.4	4.6
1961 Summer	55	233	4.2	4.6
1960/61	20	99	5.0	4.6
1960 Summer	55	267	4.9	4.4
1959/60	22	101	4.6	4.3
1959 Summer	61	250	4.1	4.3
1958/59	46	201	4.4	4.4
1958 Summer	36	145	4.0	4.7
1957/58	40	179	4.5	4.8
1957 Summer	29	128	4.4	4.9
1956/57	39	187	4.8	5.0
1956 Summer	52	279	5.4	5.0
1955/56	28	138	4.9	5.0
1955 Summer	58	290	5.0	5.0
Average roundness, 1955 Summer to 1966 Summer.......			4.5	
1942	40	193	4.8	5.0
1940	21	104	5.0	5.0
1938	31	158	5.1	4.9
1936	23	118	5.1	4.9
1935	40	196	4.9	5.0
1925	22	103	4.7	4.9
1919	55	265	4.8	4.9
1908	49	243	5.0	-
1900	33	178	5.4	-
1890	73	335	4.6	-
1880	46	2.8	4.7	-
Average roundness, 1880 to 1942....................			4.9	
1965/66 X	44	212	4.8	-
1965/66 Y	14	64	4.6	-
1965/66 Z	39	186	4.8	-
1964/65 W	25	109	4.4	-
1964/65 X	30	131	4.4	-
1964/65 Y	14	57	4.1	-
1964/65 Z	32	153	4.8	-
1962/63 Z	38	188	4.9	-
1955 Summer Z	20	98	4.9	-

No sample collected for the 1922 moraine. The till of this moraine has great variations: no one place is representative.

PHOTOGRAPHS

Plate 1

Aerial Photograph of the Recessional Deposits of the Athabaska and Dome Glaciers

This photograph is enlarged three times from the centre of Alberta Department of Lands and Forests Air Photograph number 160/5205X/2111/111. The picture was taken on September 15th, 1951, at 4.00 p.m. The scale of the original is approximately one inch to one mile. This enlargement has been cut down to match the area covered by Figure 4.

At the time of this picture, the new Banff-Jasper Highway and new access road had yet to be built. The older recessional moraines can be clearly seen in the lower right hand corner of the photograph. The "recent" moraines have yet to be deposited. Snowmobile tracks can be seen on the Athabaska Glacier.

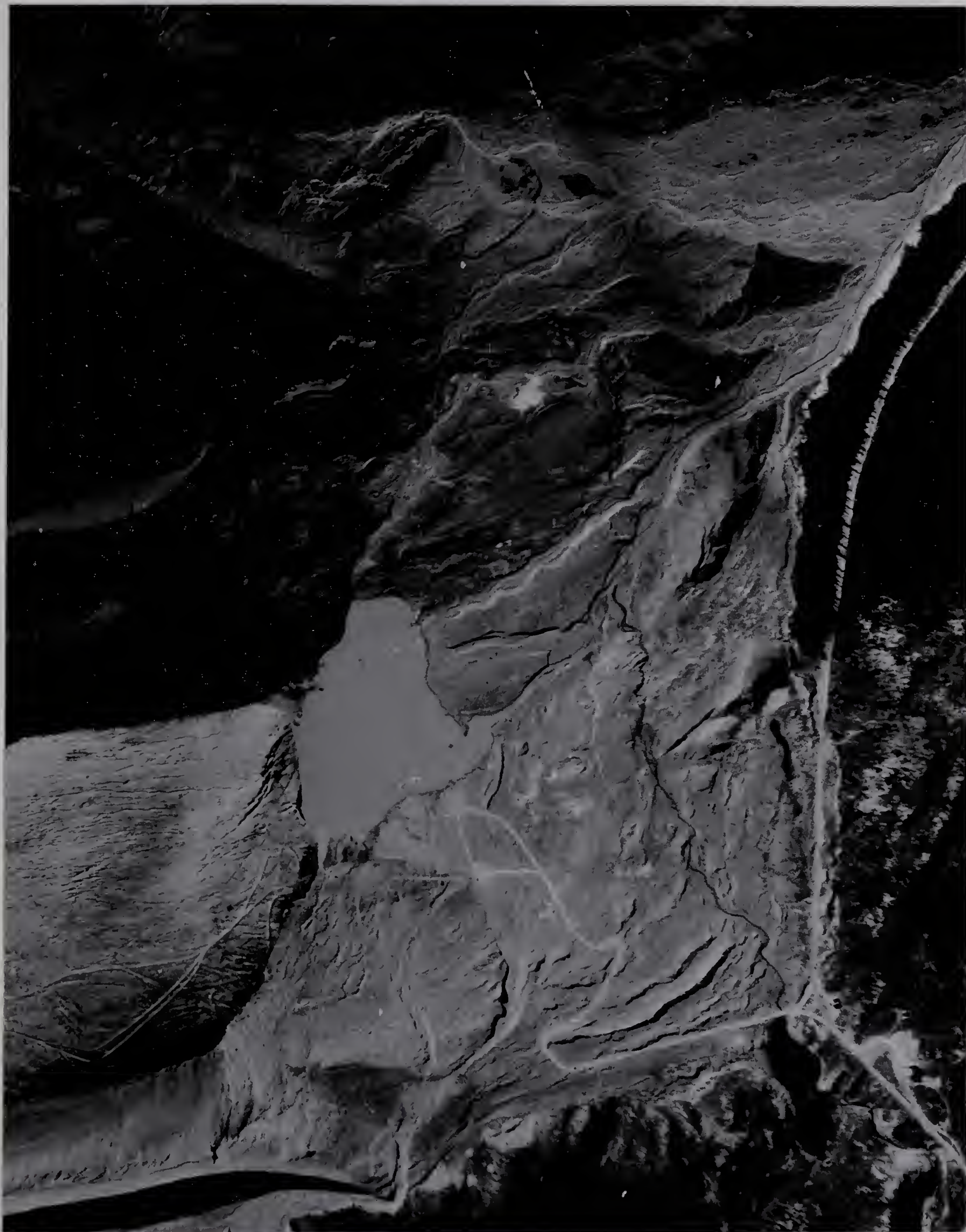


Plate 1
Aerial Photograph of the Recessional Deposits of the Athabaska and Dome Glaciers

Plate 2

The Athabaska and Dome Glaciers

This picture was taken from the south end of Wilcox Peak. From left to right (south to north) can be seen the north slopes of Mt. Athabaska, the Athabaska Glacier, the Snow Dome, the Dome Glacier, and Mt. Kitchener. The Athabaska Glacier is approximately three miles distant, and viewed from 8,000 feet above sea level, just above the tree line.

Plate 3

The Athabaska Glacier

Viewed from near the summit of Wilcox Peak (compare with Plate 2), this photograph shows the area covered by the Little Ice Age advance of the Athabaska Glacier. To the lower left are curving recessional moraines from the late nineteenth and early twentieth centuries. Through these moraines passes the road seen in Plates 17 and 18. After one mile this road leads to a car park one hundred and fifty yards in front of the glacier. Between the car park and the glacier are the recessional moraines 1955/56 to 1965/66. Other features visible are large lateral moraines, outwash areas, deltas, and a terminal lake. In the foreground the Banff-Jasper Highway and Columbia Icefields Information Centre can be seen.

Plate 4

Recent Recessional Moraines
of the Athabaska Glacier

In front of the glacier are the five moraines 1965/66 to 1960/61 (in order approaching the camera). The geological hammer and the three figures in the right background give the scale. Below the hammer are striations on bedrock.

Plate 5

The 1965/66 Moraine

The moraine has already been formed by glacier-pushing during the winter of 1965/66. Here, on June 18th, 1966, snow resting on the glacier is melting and revealing the tops of the new moraine. The figure (right middle distance) is standing on deposition from the summer of 1965.

In the background the glacier is calving into Sunwapta Lake. On the skyline is the Snow Dome.

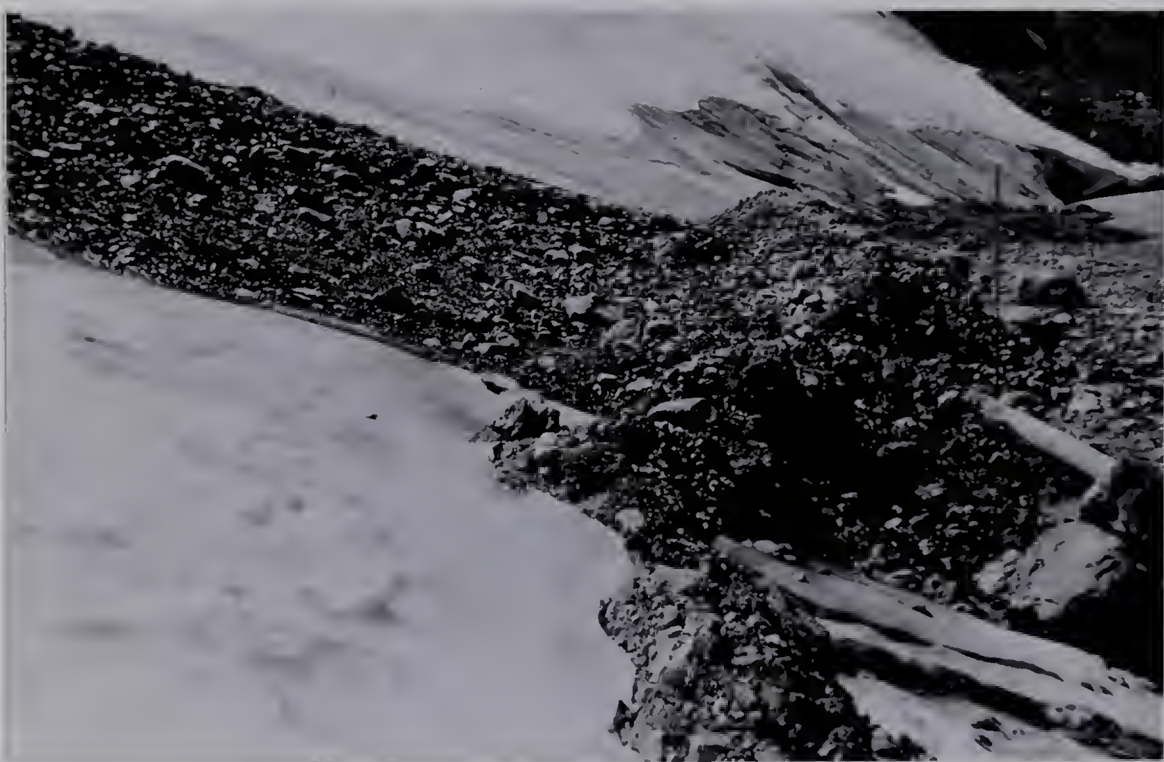


Plate 6

The 1965/66 Moraine

This photograph was taken on July 14th, 1966, at approximately the same location as Plate 5. The auger at right is six feet high. To the left of the now uncovered moraine is ablation moraine. This material can be seen in more detail on Plate 7.

Plate 7

Ablation Moraine

The auger at lower right has a half-inch diameter shaft and a one-inch diameter head. In this picture the glacier slopes away from the camera at approximately thirty degrees. The debris, which is resting on pure ice, contains mud, sand, gravel and stones as large as twelve inches across (upper centre). This material was photographed on July 14th, 1966, and was deposited as ground moraine during the following two weeks.

Compare with Plate 6, a different viewpoint of the same material.

Plate 8

The 1965/66 Moraine, Sections A to C

This photograph looks at right angles toward the sections A to F on this moraine. Section A runs across the near foot of the moraine; section B through the line of the six foot auger and the axe (to the left); section C passes across the top of the moraine as seen here.

Plate 8 was photographed on June 14th, 1966.

Close-ups of the front face (toward the glacier) can be seen on Plates 9 to 12.

Plate 9
Front Face of the 1965/66 Moraine

Taken on June 14th, 1966, Plate 9 illustrates the front faces (toward the glacier) of sections C to F. The geological hammer gives the scale: the handle is thirteen inches long. The hammer rests across the crack opened by overturning of material, although this has not yet slumped to the foot of the slope.

Plate 10
Front Face of the 1965/66 Moraine

This is the same face as shown by Plate 9,but taken on June 20th, 1966. The light material in front of the snow on the previous illustration is also in the centre of Plate 10. Some material, which on June 14th was still overturning, has now rolled over completely and come to rest one foot above the water level. At the extreme lower left can be seen the edge of the glacier's snow cover. The glacier has therefore melted about five yards from the moraine of the previous winter.

Plate 11

Frost-heaving of the 1965/66 Moraine

Plate 11 looks down vertically to the foot of the front face (toward the glacier) of section B, as it appeared on June 14th, 1966. The crack (lower right) is one to three inches wide. This has been formed by freeze-thaw expansion.

The till is of stones ranging from half-inch to four inches in diameter. The axe is standing on a meltwater pond that refroze after several cold nights, but which at the time of this photograph was covered by one inch of water. The axe handle is twelve inches long and approximately one inch in diameter.

Plate 12

Frost-heaving of the 1965/66 Moraine

This picture, taken on June 20th, 1966, is of the same material as shown by Plate 11, but photographed at an angle and with the Athabaska Glacier to the left. The single crack shown on Plate 11 has widened and multiplied during the six days interval. The cracks are now two to six inches wide.

Plate 13

The 1964/65 Moraine

Plate 13 shows the 1964/65 moraine from section D to the footpath (located by the geological hammer and the three figures respectively). This moraine is already much smoother than the more recent deposition (Plates 8 to 10).

To the left and right of the morainic ridge is 1965 and 1964 summer deposition. Across the lake the Athabaska Glacier is calving. The date of this plate is June 16th, 1966. By June 18th, 1966 (Plate 5), the smaller of the two icebergs (to the left) had drifted away.

Plate 14
The 1890 and 1900 Moraines

Plates 14 to 17 form a left to right series showing the older recessional moraines of the Athabaska Glacier (1880 to 1942). All were taken on August 14th, 1966, but not necessarily from the same place.

Plate 14 looks along the crest of the 1890 moraine from just by the Upper Parking Lot. To the right is the 1900 moraine, here about thirty feet high. To the left can be seen part of the old access road. In the right distance (approximately one mile)is the Athabaska Glacier.

Plate 15
The 1908, 1919 and 1925 Moraines

This view was taken from the crest of the 1908 moraine, midway between the crossing of the old and new access roads. At this point the moraine is about thirty feet above the inter-moraine areas (marked by a woodpile). To the right are parts of the 1919 and 1925 moraines. The old access road passes left to right between them. Plate 15 shows nearly the full width of the Athabaska Glacier at the time when most of the snow cover had melted.

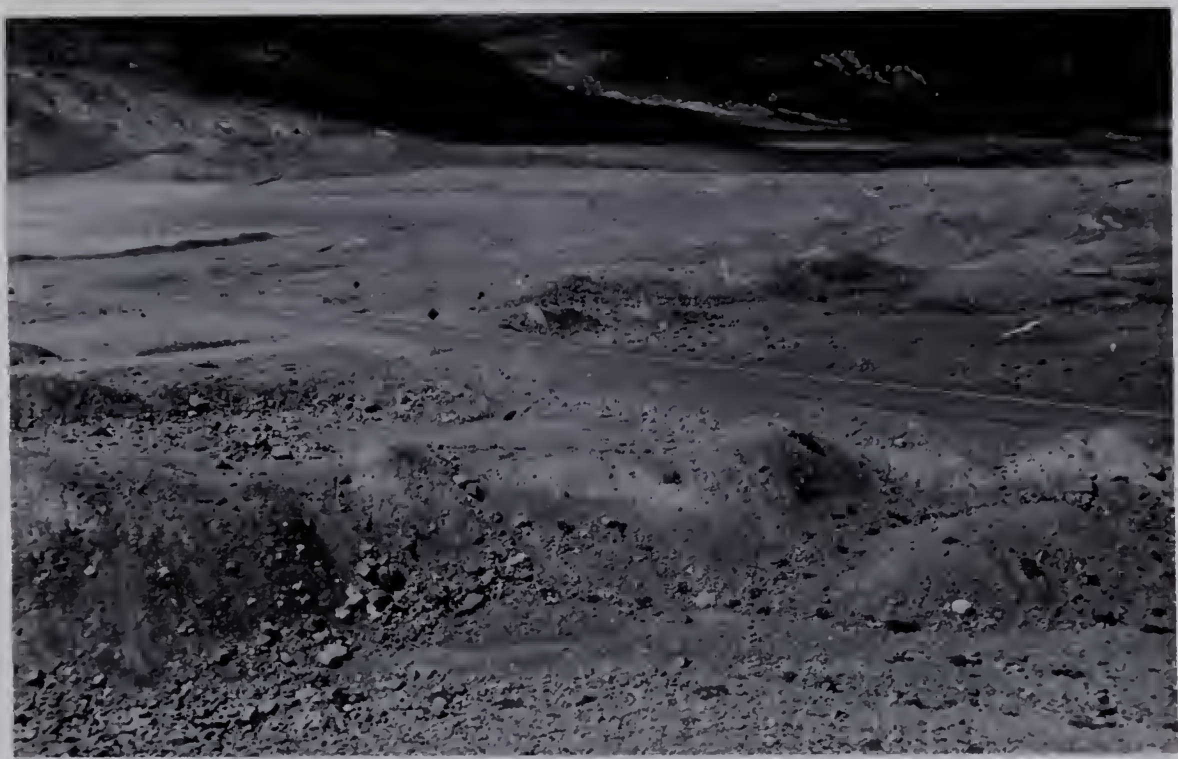


Plate 16
The Moraines 1908 to 1942

Plate 16 looks from the crest of the fifty feet high 1900 moraine, across the 1908 and 1919 moraines and the junction of the old and new access roads (between the signposts). Beyond and to the right of the signposts is the 1935 moraine. In the left distance (about one-third of a mile) is the 1942 moraine and the terminal lake of the Athabaska Glacier.

Plate 17
The 1900 and 1908 Moraines

This photograph looks along the crest of the large 1900 moraine as it crosses the new access road. In the background is the Columbia Icefields Information Centre and its parking lot. The Cadillac is crossing the line of the 1908 moraine, at this point parallel to the 1900 moraine.

Plate 18

Cross Section of the 1964/65 Moraine

Although taken out of focus on August 14th, 1966, this photograph, of the stream-truncated east end of the 1964/65 moraine, shows that this moraine at least has no internal sorting of material. The surface appears more stony since rain and snow melt have washed away the finer particles. The shovel (left) and hammer (right) give the scale. Plate 19 is of the same section as Figure 31, illustrating the location of samples 1964/65 W to Z.

Plate 19

Cross Section through 1955 Summer Deposits

Plate 19, taken on August 16th, 1966, shows the location of till sample 1955 Summer Z (marked by the hammer). This picture is of the bank cut through till by the outwash stream which flows right past the Lower Parking Lot and eventually to the terminal lake. Like Plate 18, this photograph reveals that the till is unsorted at depth. In the background is Mt. Kitchener.